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EVALUATION OF THE KEYSPARES SPARING MODEL USED FOR THE PROPOSED SPACE STATION

THESIS

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Timothy I. Mills

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Abstract

The purpose of this study was to evaluate the Keyspares sparing model used to calculate on-orbit spares for the proposed Space Station. The study had five basic objectives:

1. Present and describe the Keyspares' sparing model and its assumptions.

2. Locate, analyze and discuss the theoretical literature that either supports or refutes the Keyspares' assumptions.

3. Produce a simulation of on-board failures and resupply of the Space Station's Electrical Power Unit (EPU) system.

4. Run the simulation using Keyspares' assumption of a constant Orbital Replaceable Unit (ORU) failure rate and compare the simulation results with recommended ORU stockage policies of the Keyspares model.

5. Run the simulation again while varying the ORU failure rate distributions, and determine the difference resulting from each variation.

The study found that the Keyspares model underestimates the number of spares required to maintain the Space Station's EPU system continuously operational,

and recommends that further analysis of the Space Station's sparing requirements and improvements in simulating the Space Station environment be conducted.

Analysis of the simulations found that the Space Station experienced downtime when the EPU ORU failure distributions were assumed to be either normal or exponential, but not for the Weibull distribution (S<1). Also, the study suggests that the level of system redundancy was a driving factor in the amount of system downtime experienced.

Finally, this study recommends that an integrated, "upfront" approach be applied to solving the logistical support problems of the Space Station to ensure mission achievement at the lowest possible cost.

EVALUATION OF THE KEYSPARES SPARING
MODEL USED FOR THE PROPOSED
SPACE STATION

I. INTRODUCTION

Background

> The race for space began when the Soviets launched their first Sputnik satellite in October 1957. The United States countered with its Explorer I satellite four months later and, since then, has put men in earth orbits, landed men on the moon, and walked in space (6:12).

Although these technological achievements are spectacular, the cost is enormous (6:12). For example, The Space Shuttle took approximately $14 billion (in 1985 dollars) to develop and costs from $42 million to $150 million per flight (20:48). These extremely high prices pose a serious threat to the future of the United States Space Program.

If the United States is to maintain its technological leadership in space, managers of space programs must find effective ways to reduce costs while providing required system capabilities and support (6:12). To accomplish this goal, program managers and logisticians should employ the principle of integrated logistic support (ILS) management. This means managers must consider logistic support elements, such as on-board equipment needs, launch configurations, transportation requirements, and supply

support up-front, during design, not after the system is operational (6:15). Space System Logisticians must use integrated logistics support principles now if they are to cost-effectively support the U.S. space program beyond the year 2000 (6:14). This up-front approach to minimize total life-cycle cost (LCC) represents the major challenge to space system logisticians.

In the early stages of space exploration, the prime consideration was to develop a vehicle that would leave earth's atmosphere and go into a predetermined orbit around the earth, the moon, or another planet. The technological and logistical problems for such a goal were countless. It was soon evident that developing a space vehicle required not only the most advanced technology but further advances in all the scientific disciplines. "Today, most of the problems of developing a space vehicle for launch and orbiting purposes have been very well solved, and one of the next steps in space technology is logistics" (7:1).

Just having a vehicle orbiting in space for a period of several months is not enough; users need a means of resupplying it. In order to sustain the crew and the mission, it will be necessary to supply and resupply fuel, food, spare parts, and all other requirements for preserving life and safely returning the crew back to earth (7:1).

In January 1984, President Reagan directed the National Aeronautical and Space Administration (NASA) to develop a permanently manned space station within a decade. Its mission is to provide a space laboratory for conducting scientific and technological experiments. The Space Station will also act as a permanent observatory, and as a transportation node for satellites between orbits. The possible uses of the Space Station are virtually limitless (6:12). The Space Station will represent the United States' highest achievement in space technology well into the next century.

As essential elements of integrated logistics, supply support and requirements computation will play a major role in the cost-effective management of the Space Station Program. The ability to effectively predict supply requirements for the Space Station is one of the essential needs of the space system manager/logistician today.

One important element of supply support is determining the number of spares required to maintain the Space Station in an operational state. Since the Space Station will be a continuously operating space system, determining spare parts for critical on-board systems will be essential in providing adequate logistical support.

This study focuses on one specific Space Station sub-system, the Electrical Power Unit (EPU) system. The electrical power unit is an on-board system that provides

essential electrical power to the Space Station's living quarters and work areas (15). This system was chosen for study because it is representative of a critical, on-board, continually operating system for which spare components must be available. Since this system is a mature system, its design and the reliability of its sub-components are well known (13). Because the EPU system is so critical to the Space Station, it is comprised of highly reliable Orbital Replaceable Units (ORUs). The eventual failure of these ORUs can render the Space Station inoperable, a costly and potentially dangerous situation. Due to this fact, an accurate and effective spare requirements model is needed. This problem of accurately determining spares required to support the EPU system for the lifetime of the Space Station is what this study will specifically focus on.

Problem Statement

Outer space is an unique and hostile environment for a system to operate. Factors such as lack of gravity, scarce storage space, and the extreme distances from any support facility pose extraordinary limitations for supporting a space system. Because space is a unique environment, direct applications of classical inventory models may not adequately determine spare part requirements for a space-based system.

Currently, NASA uses a deterministic model, named Keyspares, to determine spare requirements for Space Station systems. Keyspares was developed under contract by the Boeing Corporation. This model determines overall spare requirements for specific ORUs, for the lifetime of the Space Station operation (17). A key assumption in this model is that ORUs have a rate of failure that can be accurately approximated by an exponential distribution, implying a steady, constant failure of ORUs throughout the life of the Space Station's mission (13).

Consequently, the specific problem addressed by this study is as follows: In evaluating the Keyspares model, is the assumption of exponential failures correct? If this assumption is not correct, how will that fact affect the spare requirements for the EPU system?

Research Questions

Two basic research questions underlie this study. These questions are as follows:

1. What evidence in the literature exists that the constant failure assumption underlying the Keyspares model is valid when applied to the Space Stations' EPU system? Basically, is Keyspares a good model for calculating on-board spare requirements?

2. What changes in spare requirements and lifetime EPU support occur if the basic constant failure rate assumption of Keyspares is changed.

Specific Objectives

To answer these questions, the study will meet the following objectives:

1. Present a thorough discussion of the Keyspares model, including the assumptions which it incorporates and the results that are obtained when the model is run.

2. Locate, analyze and discuss (in the literature) the theories that either support or refute Keyspares' assumptions.

3. Produce a simulation of on-board failures and resupply of the EPU system. This simulation is based on accepted design.

4. Run the simulation using Keyspares' assumption of a constant failure rate and compare the results of the simulation with results of the Keyspares model.

5. Run the simulation again while varying the failure rate distribution, and determine the differences resulting from each variation.

6. Draw inferences, based on the knowledge gained from the literature, about the meaning of the different simulation outputs.

Scope

This study is primarily concerned with identifying and evaluating the current spare requirements model used for the Space Station. Although a simulation of ORU failures was created, this simulation was not developed to

present a new spare requirements model. Rather, this simulation is employed to compare and evaluate the Keyspares model under various ORU rate of failure assumptions.

The Space Station's EPU system provided the study's data base due to its characteristics as a critical, on-board system. However, the Spare requirements analysis could be applied to any other highly critical system in which on-board spares are required.

II. Literature Review

Introduction

Development of an efficient and cost-effective supply support system for the Space Station will require logistics planning early in the program's design and development stage (11:2). An essential step to the planning phase is identifying, "up-front" the limitations the system will experience. In consideration of these limitations, the logistics manager must also develop adequate techniques and apply them to work-around the systems' limitations.

This chapter will explain the limitations for supporting the Space Station and will present the historical development of space support models, emphasizing past space programs, and models currently used in determining spares for the Space Station. A review of the literature concerning reliability and the use of simulation for supply support is also presented.

Scope

This chapter has five main objectives. The first objective is to identify the critical limitations for supply support the Space Station will experience, specific emphasis is placed on design and environmental constraints. The second objective is to identify and

explain supply support techniques and models presented in the literature that are used. The third objective is to investigate historical space systems, and analyze how these systems were supported. The fourth objective is to present the concepts of reliability and simulation, placing emphasis on how these concepts are used in supply support and spare parts determination. The final objective is to present current techniques used in determining spares for the Space Station.

Vehicle Design Constraints

The Space Station is designed to be a dynamic system. This design is based on the fact that its mission depends on who is using it at any particular time. Varying missions ranging from materials processing to astronomical observation will be common. These continually changing mission scenarios will require various supply support levels. Due to this fact, the two most restrictive limitations to Space Station support, in terms of design, are space/volume utilization and commonality of on-board assets (22:49). Once the Space Station is configured and placed in orbit, its usable volume will be finite. The currently proposed design will consist of five interlocking modules (22:47). Three modules will be used for laboratories, processing stations, and work areas. One module will be used for living quarters, and one for an

inventory storehouse (22:47). Figure 1 shows the proposed design of the Space Station (26:711).

The specific impact of this volume constraint is dependent on the mission configuration, the number of crew to support, and the duration of the mission (22:50). In determining an effective support regimen, each missions' requirements must be independently analyzed and evaluated for feasibility towards the known volume of the Space Station.

To assist in the optimal use of available space, a high degree of commonality and interchangeability of items must be achieved prior to deployment (23:2). The importance of interchangeable assets to conserve space is considered a critical element towards effective and flexible supply support for the Space Station.

> Commonality and interchangeability of both hardware and software to the ORU level or equivalent shall be required where feasible for both flight and ground systems to simplify the logistics and maintenance activities, minimize cost, and reduce spares storage (26:79).

The supply support challenge to the designers of the Space Station will be to identify those items that will be common to all Space Station customers, thereby allowing efficient use of available space.

As an additional criterion for design, initial design concepts should include on-orbit maintainability of assets

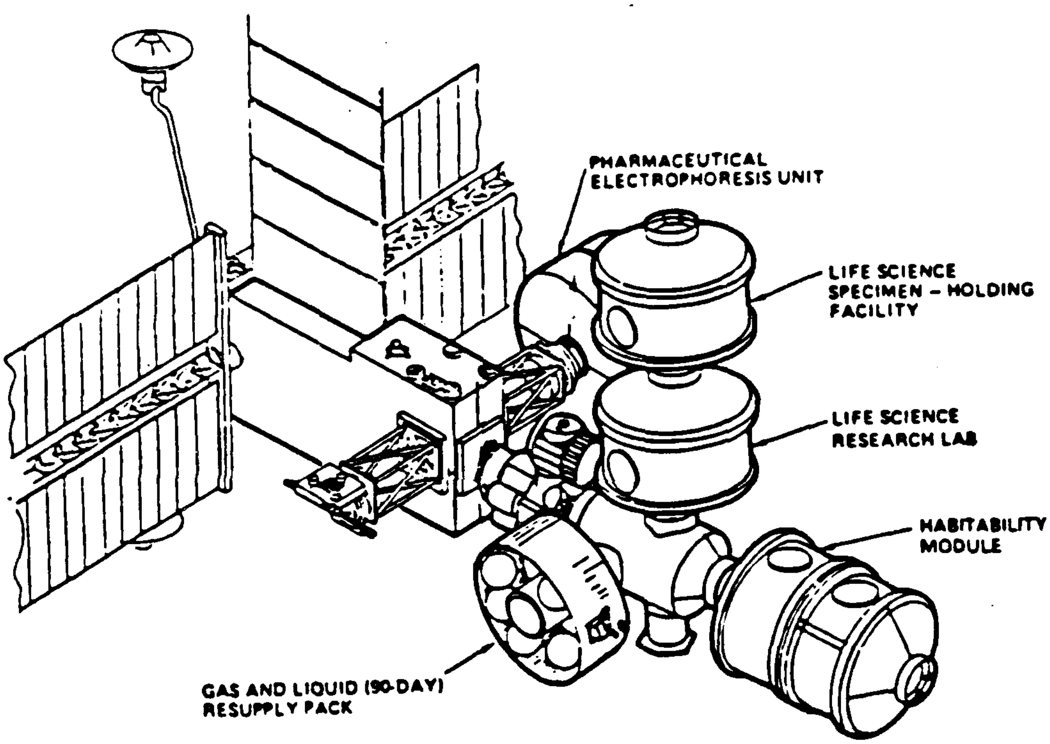


Figure 1. Design of Proposed Space Station
(26:761)

> ...with the necessary design features to facilitate future detection, isolation, corrective action, and verification of repair. Provisions should be made for tools, spares maintenance equipment, and space for maintenance work (4:27).

Not only will the Space Station have to be designed for efficient on-orbit maintenance, but its design must also address the needs of its crew. Human factors, such as sleeping arrangements, provisions for hygiene and waste management, and storage facilities for clothing and food must be addressed in the Space Station design.

Environmental Constraints

The three most restrictive constraints the space environment present are distance to a support facility, duration of operation, and space peculiar phenomena.

Distance Constraint. A critical restriction to supporting the Space Station is its distance from its primary support facility, earth. All of the logistic support centers for the Space Station will be earth-based (26:52). Since the Space Station will be placed in a geosynchronous orbit, (approximately 23,000 miles), the resupply routes will be long and expensive. Proposed orbital transfer vehicles (OTVs) will be regularly scheduled to resupply the Space Station with critical supplies (1:78). These supplies will consist of consumable gasses and propellants, foodstuffs, and ORU spares.

The distance constraint will be most restrictive during times of emergency or an unanticipated system failure. It would be impossible to expeditiously ship an asset from earth to the Space Station. Rather, the crew must make do with what they have on-board until the next scheduled OTV brings resupply. Because of this fact, it is critical that logistic managers consider component failure rates and a high supply support level when computing supply requirements (26:47).

Time Constraint. As proposed, the Space Station will be a continuously operating system. Consequently, a high degree of reliability must be built in to all its critical systems. This high degree of reliability can be achieved by means of redundancy in system design and effective determination of spare requirements (26:47). The trade-offs posed by this constraint are a balance between high system redundancy and high levels of spare components for safety and efficiency versus minimizing the constraints of space, weight, and cost. The Space Station Task Force Program Document describes this requirement as follows:

> Reliability/maintainability shall be a prime consideration in design . . . Each element should be instrumented for detection and isolation of failures to the orbital replacement unit (ORU) level. Equipment shall be designed for easy removal, repair, and replacement to the lowest level practical. Systems and sub-systems should be designed so repair can be done by removal and replacement. The ORUs shall be independent of each other so that replacement of one shall not require replacement, removal, or disconnection of another. Critical systems shall be able to undergo maintenance without

> interruption of critical services and shall be "fail-safe" during maintenance. Software shall be designed and developed to minimize maintenance costs...(26:79).

Another critical aspect of the time constraint is the shelf-life of an asset. Since the Space Station will be continually operating, any support model must consider the useful life of a component and plan for the replacement and turn-over of "over-age" assets (7:437).

Space Environment. To understand the problem involved in manned space flight, we need a thorough knowledge of the environment in which these missions are conducted (7:27). Outer space is not simply a vacuum of emptiness. The Space Station must be prepared to encounter such configurations of matter as neutral and ionized atoms, dust particles, and larger meteorites. Other peculiar attributes of the space environment, such as radiation, microgravity, and extreme temperatures will also be present (7:27). These environmental phenomena will present restrictions as to the type of asset that can be stored on-board and should be considered in any supply support model.

Historical Supply Support of Space Based Systems

Overview. In analyzing the support of historical space missions, a gradual trend toward complexity is apparent. The earlier "space probe" missions' support requirements were negligible to the latter space systems of Skylab and the Space Shuttle. Longer duration and increased

complexity of the mission greatly influenced the requirements needed for a successful mission.

This section presents the evolution of support for these space systems. Each system will represent the evolutionary progression of space exploration. The systems presented are satellites and space probes, the Apollo program, and the NASA Skylab space station program.

Satellites & Space Probes

In the early days of space exploration, space probes were the primary space missions. Even today space probes and satellite deployments represent the bulk of the United States' space program (24:31).

In these earlier missions, supply support was an inconsequential element toward the overall mission. These probes only had to be configured and supported for a short period of time. Consequently, the redundancy requirement for mission systems was low; only enough capability had to be maintained to complete the specific mission (24:33). No maintenance capability was required: if a system failed it was simply thrown-away. Later, as the expense of systems and the complexity of missions increased, integrated supply support became necessary.

> The days of the throw-away satellites are swiftly giving way to a new concept of on-orbit maintainable satellites (24:33).

Recently, the costs of designing, building, and launching satellites have increased exponentially (24:33).

This situation has forced designers of satellites to consider the total life-cycle cost of the system. As a critical element of life-cycle cost, supply support of satellites has changed in the past 20 years. Today, extensive inventory databases are maintained to identify and manage critical satellite components (24:34). New support concepts, such as on-orbit maintenance of components and increased redundancy/reliability of systems, have been introduced with a noticeable impact of minimizing supply support and decreasing total life-cycle cost (24:34).

Overall, supply support of satellites and space probes has progressed. Support considerations are integrated early, during design, to minimize cost. Still, these systems require little support. There is no human crew to consider and support. Also, these systems are designed to be compact. Therefore, all available space is efficiently used (24:35). With the advent of manned space missions, more elaborate and in-depth support of space missions was required.

The Apollo Program

Program Description. The Apollo manned space missions spanned more than one decade. These missions were a giant leap forward from the earlier earth-orbiting and space probe missions (25:52). From a supply support viewpoint, the Apollo missions represented a quantum leap

in system support requirements. New support requirements were necessary for many unique mission aspects, such as the following:

1. Support of a crew was necessary. Consumables, living quarters, and waste support were now required.

2. The duration of the mission had now increased. The concept of asset reliability and maintainability was necessary for a safe and successful mission. As a result, the concept of interchangeability and commonality of assets was introduced and applied. This resulted in the need for management of reparable ORUs and determining pipeline spares for on-board resupply.

3. Mission configuration was dynamic. The earlier space missions were static. These missions were designed to orbit the earth and return. Later, the Apollo missions had a multi-stage configuration. These missions were designed to travel to the moon, land and explore the lunar surface, then return to earth. This dynamic, multi-stage nature greatly added to the support requirements. Each segment of the mission experienced different environmental constraints. For example, the initial supplies had to be compactly configured and light enough to meet launch-weight limitations. Uniquely critical supplies were required for exploration of the lunar surface (environmental lifepacks, lunar rover). Finally, enough

critical supplies such as food, water, and fuel needed to be conserved for a safe journey home.

<u>Apollo Support Models</u>. The inventory models applied in the Apollo program used a combination of support techniques (23:1). Classical economic-order-quantity (EOQ) models were used to determine consumable levels of food and daily supplies. Dynamic programming optimization models were applied for scheduling and supply utilization rates. New concepts such as on-orbit servicing and resupply were first applied in the Apollo missions. Consumables, such as gasses, liquids, and propellants were serviced by the crew, who also performed minor maintenance of ORUs. Overall, the Apollo program was the first space mission in which integrated logistic support was successfully applied.

<u>Spares Selection Model</u>. In a study conducted by the Rand Corporation, a procedure was developed to determine selection of spares based on increasing overall system reliability. This technique added spare assets to a proposed "blastaway kit" in support of the Apollo spacecraft. The objective of this technique was to maximize total system reliability within a specified weight constraint. This study suggests that

> ...the relationship between equipment failures and the spares aboard a spacecraft appears to be the primary factor in determining the impact of spares on mission success and crew safety (28:6).

This technique used a Lagrangian multiplier marginal analysis approach to add critical assets to the blastaway spares kit. The goal is to minimize the expected difference between the spares required as a result of failure and the spares available within a specified weight allowance (28:6). In order to satisfy this goal, each candidate spare of each module type is assigned a "selection index." This selection index parameter is calculated as follows (28:9-10):

$$a_i\ (k_i) = 1/w_i \sum_{y=k_i}^{\infty} p_i\ (y) = 1 - P_i\ (k_i-1)/w_i \qquad (1)$$

where:

$a_i\,(k_i)$ = The selection index for the Kth spare of module type i

w_i = The weight of each module of type type i

$p_i(y)$ = The probability of exactly y failures of module 1

$\sum p_i(y)$ = The probability of n or fewer failures of modules of type i occurring during a normal mission.

Based on the above criterion, the blastaway spares kit is derived by selecting spare assets in the order from highest to lowest values of their selection index until the desired kit weight is reached.

For example, if the fifth largest selection index is $A_6(2)$, then the fifth module to be added to the

> spares kit is the second module of type six. Thus, the selection index for a particular module can be interpreted as a priority rating for that module in the selection of spares (28:11).

The basic result of this study is the development of a simple procedure for selecting a spares kit that maximizes, within a weight constraint, a mathematical measure of reliability for a constrained system (28:V).

Basically, this procedure is the addition of spare modules or redundant elements to the blastaway kit, in the order of their selection indexes, until the desired weight is reached. The selection indexes for each spare or redundant element can be readily calculated from the mission profile and the weight and reliability data on each module type (28:V).

NASA Skylab Space Station Program

Overview. The United States' first attempt at an autonomous, continually operating space system was the Skylab experimental space station. The NASA Skylab was actually only operational for about nine months in 1973 and 1974. The Skylab space station seemed to signal the beginning of an era where serious use of the near-earth space environment became a focal point for scientific research (25:37). Skylab conducted the first outer space experiments in materials processing and evaluated the effect of the space environment on human physiology (25:37). After the last mission in 1974, Skylab circled

the earth unoccupied for the next five years. Finally it fell to earth late in 1979.

Supply Support. Although Skylab was operational for only a short time, it provided much important data concerning support and the space environment. In terms of supply support, Skylab presented many challenges. First, Skylab was the first continually operating system (25:40). High reliability of system components was required to efficiently support these long missions. To operationally achieve this requirement, design engineers introduced the concept of modularity and scheduled on-orbit maintenance/servicing (23:2). Design modularity was introduced to critical sub-systems so that routine servicing could be accomplished by simply changing a system module. This technique minimized the amount of maintenance that had to be done as well as reduced the cost of maintaining the Skylab space station. A second benefit realized by modularity and on-orbit maintenance was the decreased requirement for redundant systems. This also had the additional effect of increasing the total storage volume, allowing a greater depth of critical supplies and system spares. Second, Skylab was the first space program to support a large crew for an extended period of time (25:41). Some missions lasted over seventy days, with crews of up to eight people. The crews' support requirements were integrated "up-front" during the

mission configuration (25:42). Modified classical consumption models as well as optimization techniques were applied to support the crew. Each crew members' requirements were calculated in detail prior to launch, with very little deviation allowed. Finally, the Skylab missions presented the first opportunity to analyze the long term effects of the space environment towards the crew and system components (25:41-42). Specifically, the effects of solar radiation and micro-gravity were studied, and components were modified and redesigned to overcome these environmental phenomena.

Overall, the Skylab space station represents the closest U.S. model to the proposed Space Station. The design and mission configuration are similar, and the supply support models required for the Space Station will closely approximate the models applied during the Skylab missions.

Related Studies of Constrained Support Systems

Throughout the literature, there are many support models and heuristics developed in support of constrained systems. For instance, models have been developed to determine support for shipboard, submarine, and aircraft systems. Much like the space environment, these systems are constrained in the number of spare assets they can carry. Constraints such as volume and limited storage, total allowable weight, size and configuration of the

asset, and shelf-life all pose a critical limitation to the number of spare assets available to perform the required mission. This section reviews some of the historical techniques employed to support systems with constraints.

Haber and Sitgreaves' Studies

In a series of articles, Haber and Sitgreaves determined the depth and range of repair assets required to perform a shipboard mission. Haber and Sitgreaves take an approach which predicts the demand of reparable assets for both low and high usage assets. The motivation for their studies is to predict the demand of reparable assets to insure proper support of ships and submarines (10:297). Much like a space based system, ships and submarines are self-contained systems isolated from immediate logistical support. All required supplies and spares must be on-hand and readily available in order to support the mission. Also like the Space Station, ships and submarines are constrained in the amount of storage space available for critical supplies. Therefore, it is essential that demands for supplies can be accurately forecasted prior to going out on patrol.

Demand Rates. In these studies, Haber and Sitgreaves use several approaches to determine reparable usage rates, thereby allowing the supply system to provision these systems on a priority basis. "A usage estimate is an

estimate of the number of units of a particular part that will require replacement per unit time period per unit of installed configuration" (10:297). An important aspect of these studies is that the authors' approach does not just look at how often a reparable part is demanded, but also the characteristics of its demand pattern. "For example, typically the majority of those parts used by a component one year are not the same parts used in the next year" (10: 298). Therefore, understanding demand characteristics of a component, not the number of times demanded per unit of time, is the essential element in accurately predicting the range and depth of provisioning for a constrained system.

This approach to understanding demand characteristics can readily be applied to sparing for the Space Station. Since the Space Station has many new systems and component ORU's, accurate demand histories are not always available, but by pooling component failures and estimating lifetime reliability of components, analysts could characterize the systems' demands and estimate lifetime support requirements.

Flyaway Kits

Overview. Flyaway kits are stand-alone critical spares packages used to support aircraft deployments to remote locations for a specified time duration. Each kit must be adequately stocked with the necessary depth and range of spare assets to insure the maximum protection

against stockouts likely to ground combat aircraft (12:1). In the Rand Corporation study A Preferred Method For Designing A Flyaway Kit, four methods for designing a flyaway kit are tested and evaluated (12:1). The first method determined the kit configuration based solely on demand. The second method adds the influence of increased weight to the kit. The third adds demand for successive units of each included asset. Finally, the fourth method considers the essentiality of different assets to aircraft operations. In each method, a successive refinement is added to account for the kit's weight, volume and operational constraints.

In the first method, an average of thirty days of consumption is considered. Obviously, no consideration of overall weight and aircraft lift capacity is made. The second method takes into consideration both the demand and weight of each asset, requiring a trade-off between the asset's expected demand versus its weight. The third method also considers demand history and weight but prioritizes kit assets as to how well they reduce predicted stockouts. In this approach, marginal analysis is used to determine the additional benefit an asset will provide per extra pound of weight (12:2). Finally, the fourth method introduces the criteria of essentiality or relative importance to a mission capable aircraft to each additional kit asset. The authors conclude that taking

this fourth approach provides the best results in determining an effective flyaway kit configuration.

In related flyaway kit studies, this marginal analysis approach is used and improved upon. Additional factors, such as determining the expected demand of an asset and improvements on defining essentiality have shown to be important considerations in flyaway kit configuration (16:1).

Summary. In summary, the method of designing flyaway kits consists of adequately specifying how to best allocate the available spare part resources. The significance of the flyaway kit studies to the Space Station problem is the use of marginal analysis towards prioritizing spare asset stockage for a constrained system.

Rand Studies Of Space Support

This section summarizes two Rand studies concerning support of space-based systems.

The first study, A Mathematical Model of Supply Support for Space Based Systems is by Freeman, Gogerty, Graves, and Brooks. In this study, the authors developed a methodology to evaluate various aspects of logistical supply support for space systems. This methodology assumes that a fixed, well-defined schedule of operations for the daily living requirements and on-orbit activity is known. As a result of these known activities, daily supply support demands are calculated (8:1). The central

purpose of this study is to determine a resupply schedule to meet the specified mission demands. In this scheduling model, support assets are given an earliest and latest time in which they must be delivered. These due dates are determined taking into consideration constraints such as storage capacity, weight, and a myriad of environmental factors. This schedule also takes into account the dependency of the assets on factors such as power availability, storage, and sub-dependency to other assets.

The logistical model employed uses a simple, non-linear discrete programming algorithm to plan a series of resupply trips. Each resupply trip is given requirements specified by the mission configuration and the constraints of that mission. For example, a specific mission may require supplies for four men for ten days, given a weight and storage capacity constraint. Assuming that each mission will have a unique configuration and systems constraint, the resulting algorithm provides a detailed schedule of operation. This schedule is then translated into supply requirements for the duration of the mission.

The second study, Logistical Implications of an Astronomical Observatory on the Moon is by Freeman, Moore, and Schilling. In this study, support requirements are simulated for constructing a manned lunar base over an eight-year period. This study attempts to identify the

logistical bottlenecks and deficiencies that would be experienced in such an undertaking. The analysis of this study consists of running two computer simulations to determine the necessary resupply delivery schedules, and to provide the total life-cycle logistical costs of the simulated mission.

> Detailed input parameters (to the simulation) consider such aspects as capacities of launch vehicles and spacecraft, the number of launch pads and pad turnaround times, scientific mission objectives, and allowable times for unattended storage of expendable goods (9:v).

Reliability

Overview. Spares requirements are dependent on the component's inherent reliability. When a component fails to work when required it is said to be unreliable. When this situation occurs, a replacement component is needed in order for the system to function. Replacements or spares are costly and occupy valuable storage space on the Space Station. In order to minimize the number of spares required, a review of the concepts of reliability is necessary.

Reliability Theory. Blanchard defines reliability ". . . as the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions" (5:12). The plot of the reliability probability over time is known as the reliability distribution. Since it expresses the

probability of surviving over any specified interval, it is also known as the survivor function (21:8). The reliability function R(t) is expressed as

$$R(t) = 1 - F(t) = \int_{t}^{\infty} f(x)\,dx \qquad (2)$$

where F(t) is the probability that the system will fail by time t (5:23).

Throughout the literature, the failure distribution function F(t) has been assumed to follow many well-known probability distributions in describing the failure characteristics of components over time.

Exponential Distribution. The most widely used distribution in discussing reliability of components is the exponential reliability distribution.

$$R(t) = e^{-t\lambda} \qquad (3)$$

where t is the operating time (cycles) and (λ) is the failure rate (5:26).

Failure Rate. "The rate at which failures occur in a specific time interval is called the failure rate" (5:25). The failure rate (λ) is expressed as

$$\lambda = \frac{\text{Number of Failures}}{\text{Total Operating Hours}} \qquad (4)$$

For example, if five components fail over a total operating time of 2000 hours, the failure rate (λ) is equal to 5/2000 or .0025.

The literature also shows that the reciprocal of the failure rate (λ), is equal to the mean of the exponential

distribution (5:26). This is commonly called the mean time between failure (MTBF) of repairable items in useful life (3:33). If we use the example of five failures with 2000 hours of operating time, then the MTBF is equal to 1/.0025 or 400 hours.

MTBF is widely used as a measure of reliability and indicates how reliable a component is during its useful life (3:34).

Rimpo points out that since the "exponential distribution is easy to fit the data, it has often been misapplied to situations that require a more complex distribution" (21:9). Several more complex reliability distributions are useful in applying hazard theory and the bathtub curve to systems analysis.

Hazard Theory and the Bathtub Curve

Reliability theory identifies three types of failure characteristics: infant mortality, useful life, and wearout (10:10). These three failure characteristics, when plotted using the hazard rate, form the classical "bathtub curve" (10:10).

The hazard function, H(t) is the instantaneous failure rate of an item at age t, it is defined mathematically as (19:53)

$$H(t) = f(t) / R(t) \tag{5}$$

The three failure characteristics are shown to form the bathtub curve in Figure 2.

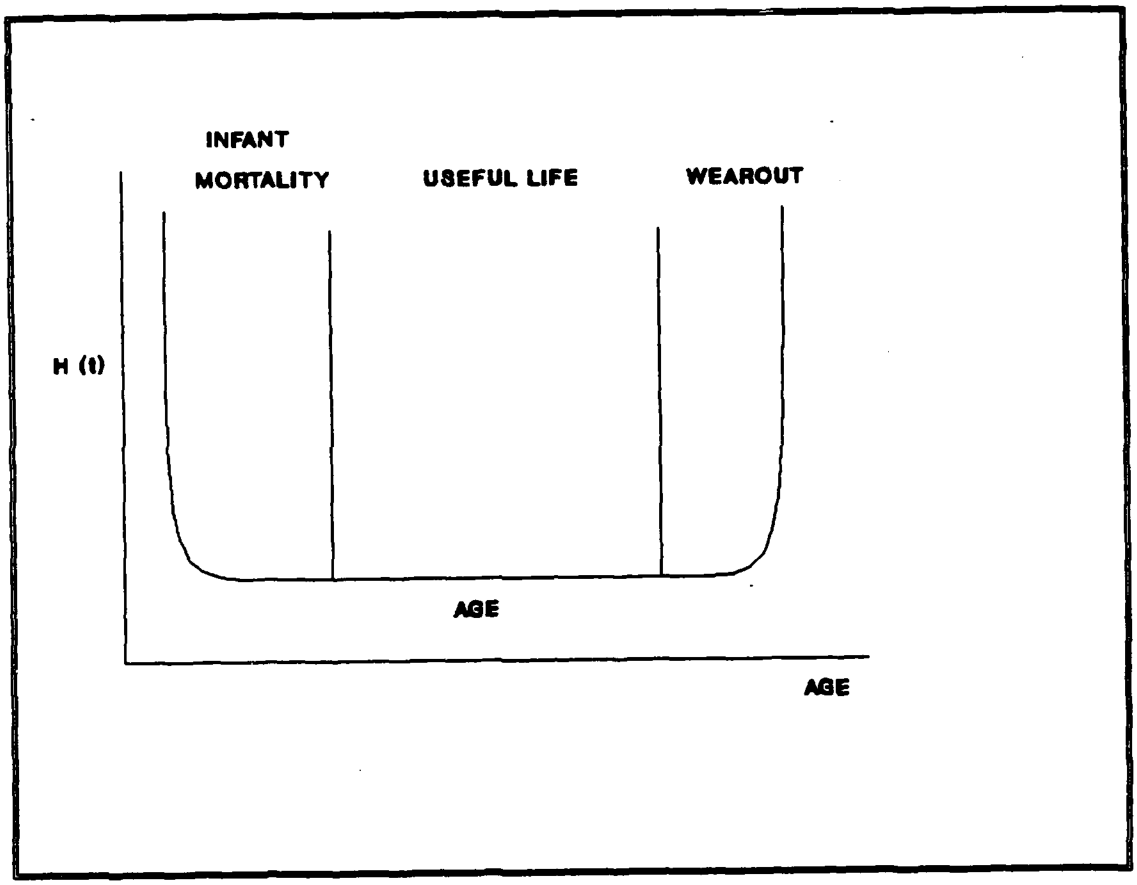


Figure 2. The Bathtub Curve

Infant Mortality. The first region of the bathtub curve, infant mortality, is characterized by a large number of failures early in a components' life. Infant mortality of a component can result from poor quality control or sub-standard parts (21:12). This region of the bathtub curve exhibits a decreasing failure (hazard) rate, due to the gradual reduction in failures over time.

Weibull Distribution. A statistical distribution that can represent a decreasing hazard rate is the Weibull distribution. The Weibull distribution was introduced in 1951, by Swedish statistician Waloddi Weibull in order to calculate the tensile strength of steel (19:44). The Weibull reliability function is defined over non-negative time intervals and is expressed as

$$R(t) = \exp(-(\lambda t)^{s}) \tag{6}$$

where

λ = component failure rate

t = time interval of the study

s = the shape parameter of the distribution

If the shape parameter s is equal to one, then the equation reduces to the simple exponential distribution. When s is less than 1, then the hazard function is characterized by a decreasing failure rate over time, representing infant mortality of components.

Useful Life. At the bottom of the bathtub curve, the hazard function is a flat line; this region is called

"useful life" and is characterized by a constant failure (hazard) rate (19:53). Since the exponential distribution has a hazard rate that is constant over time, it is used to characterize component failures during their useful life phase (21:12).

Wearout. The third type of failure characteristic is the wearout phase. In this region of the bathtub curve, components fail at an increasing rate due to aging. Increasing failure rates are indicative of component wearout patterns (21:12). Some common distributions that have an increasing failure (hazard) rate are the Weibull and gamma when their shape parameters are greater than one (19:53). The normal distribution always elicits an increasing failure rate, and is the distribution used in the present study to represent this region of the bathtub curve. Figure 3 shows the hazard functions of three distributions that characterize the three failure regions of the bathtub curve. The Weibull hazard function with $S < 1$ characterizes infant mortality. The exponential hazard function characterizes constant failures during normal useful life. Finally, the normal hazard function characterizes wearout or increasing component failure.

Simulation in Inventory Modeling

Overview. When investigating supply support techniques, relevant information on the problem may not always be available. Parameters such as lifetime demand,

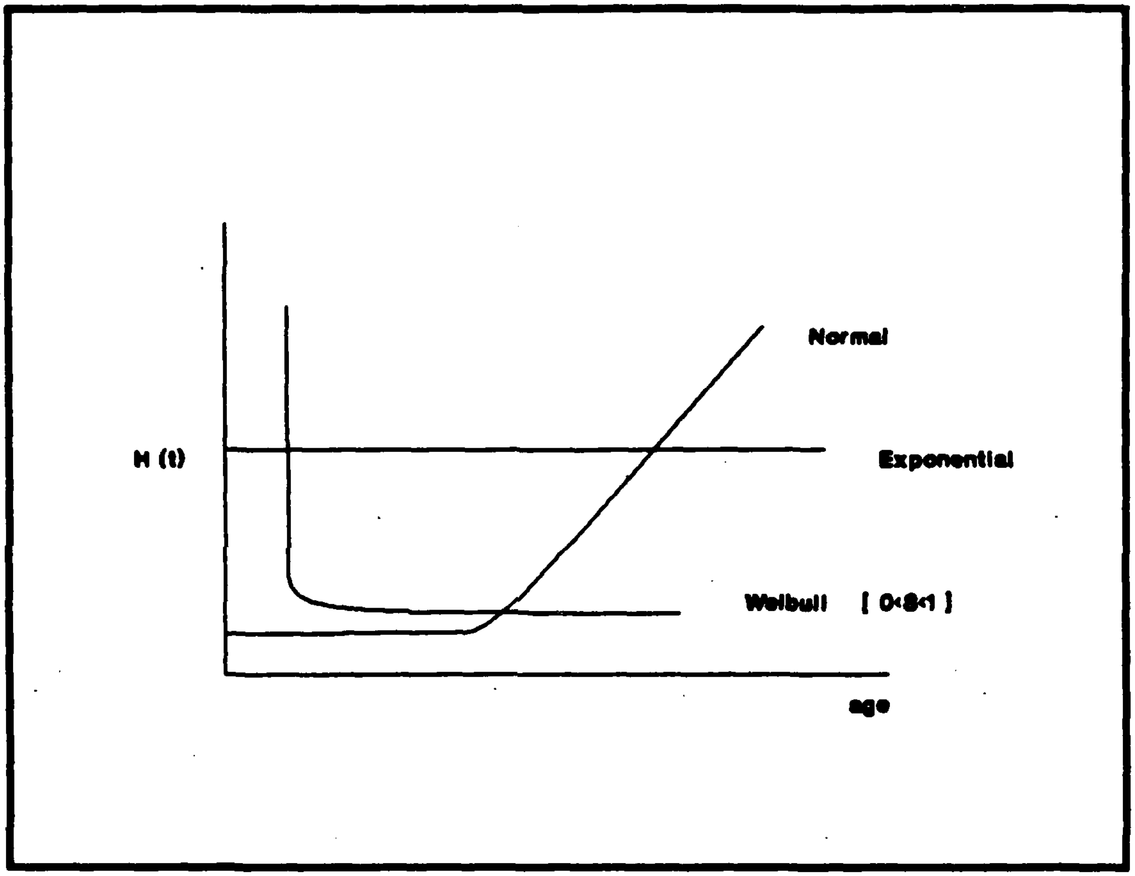


Figure 3. Hazard Functions for the Exponential
Normal and Weibull Distributions

order and shipping time, or component failure rates may not be adequately defined. When unknown system conditions exist, the valuable technique of system simulation is often useful. This section reviews some of the literature concerning the use of simulation in inventory modeling.

Simulation Studies. In their article, The Simulation of Inventory Systems: An Overview, Banks and Malave conclude that simulation can be an effective tool in modeling and analyzing inventory systems. They classify six categories where simulation is an effective tool. Two of these categories that relate to this study are comparison of models and verification of analytical solutions.

In their study, Herbert and Deckro present a simulation based comparison of several different inventory lot-sizing models under various stochastic conditions (2:285). The purpose of this study was not only to investigate the performance of inventory lot-sizing models under stochastic conditions, but also to identify the general stochastic conditions for which each lot-sizing model is "best-suited" (2:285).

In a study conducted at the Air Force Institute of Technology, Coleman, Masters, Pankonin and Peterson simulated the performance of an inventory system with expected backorders to determine whether the assumptions of of theoretical inventory models led to significant errors

in estimating backorders (2:286). They concluded that the assumptions of independent and randomly distributed leadtime about a stationary mean are frequently invalid, thereby reinforcing the usefulness of simulation in verifying model assumptions.

Finally, Banks and Malave present three benefits from using simulation in inventory models (2:286).

> 1. Simulation models can be constructed according to the environmental conditions of the problem under study so that a realistic analysis can be performed.
>
> 2. Once a simulation model has been developed, it is easy for the user to perform sensitivity analysis as well as compare different alternatives.
>
> 3. While constructing the simulation model, the user obtains a deeper understanding of the problem environment.

These simulation techniques will be used to test a spares model for the Space Station.

Current Spare Support of the Space Station

Overview. The current support models used to determine ORU spare requirements for the Space Station vary significantly in how they evaluate spares. The first method, Simspares, is a simulation based method that simulates the on-orbit environment of the Space Station. The second method, Keyspares, is a deterministic computer algorithm that predicts the lifetime failure rates of ORU's. Based on these failure rates, the algorithm computes the sparing requirements for lifetime support.

Simspares. The Simspares simulation model is a stochastic process algorithm developed by the Boeing Corporation. This model is used as a front-end logistical analysis model to determine the number of on-orbit spares needed per mission, subject to user-defined system constraints (17). The sparing algorithm used is based on a classical Poisson demand distribution with failure rates determined exponentially. The user of this model defines the mission configuration in terms of duration, number of personnel, and resupply schedule. The ORUs to be analyzed are also selected by the user. Specific ORU parameters, such as quantity per spacecraft, mean time between failures, cost, and essentiality are also defined and entered into the model by the analyst. The heart of the Simspares program processes these input parameters and generates a simulation of the Space Station operations. In this simulation, operational events, such as ORU failures and overall resource utilization are evaluated. With these calculations, the overall spare requirements are determined. Output parameters, such as time to failure of an ORU, the cost of the sparing configuration, and the overall gains in system reliability, are presented for management evaluation (17).

Some of the applications of the Simspares Program are as follows:

1. Simspares measures the supportability of the constrained space systems.

2. Simspares can simulate "what-if" operational scenarios, thereby evaluating unique conditions and system environments.

3. Simspares can be used to determine the requirements for planned maintenance actions.

4. Simspares is used to optimize reliability and maintainability design requirements, up-front prior to system development. An alternative Space Station sparing method is Keyspares.

Keyspares Sparing Model

Overview. The most current model used by NASA to determine lifetime spare requirements for the Space Station is the Keyspares sparing model. The Keyspares sparing model was developed by Jim Werpy of the Boeing Aerospace Corporation under contract for the Kennedy Space Center (KSC) (15). The purpose of the Keyspares computer program was to determine initial spare requirements of on-board ORUs for the projected lifetime of the Space Station (27). According to Werpy, the Keyspares sparing program was created to "provide a quick and dirty method to determine lifetime Space Station spares - up-front, in order to evaluate the logistical requirements of on-orbit ORUs" (27).

The projected number of spares, as estimated from Keyspares, would be stored at the Kennedy Space Center and not on-orbit (27). In a sense the spares determined from Keyspares would be filling a space system support pipeline, where the spares would be stored at earth facilities. The only time spares would be stored on-orbit is when a replenishment mission was conducted prior to an ORU failure (27). Usually, in a situation where an ORU was projected to fail, a preemptive changeout of components would be conducted (27). Werpy points out that

> The Keyspares program does not take into account the weight, size, or cost of spares, nor their impact upon the Space Stations' logistical considerations. It only evaluates the number of spares needed to support the projected life of the Space Station (27).

Model Description. The Keyspares sparing model is a FORTRAN based computer program designed to provide a deterministic estimate of spares required to support an ORU for the life of the Space Station (27). The Keyspares program estimates the number of spares needed in a two-stage calculation. First, Keyspares calculates the number of failures an ORU will experience during its operational lifetime. Second, using this estimated failure rate, Keyspares employs a computer algorithm to calculate the number of spares needed. The Keyspares' computer program is presented in Appendix B.

The Keyspares computer program is a user interactive program, where the end-user must provide ORU and resupply information in order for the program to work.

Input Parameters. The following list is the model input parameters needed for Keyspares (14:D109):

Resupply Cycle Time. This input is the designated number of days between scheduled orbiter resupply missions. This input is limited to 45, 90, or 120 days between resupply. The default value is 90 days between resupply.

Installed On-Orbit Quantity. This is the quantity installed of a specific ORU under analysis.

ORU MTBF. This is the design mean time between failure of an ORU under analysis, as specified by the ORU manufacturer.

Average Annual Operating Hours. This is the average number of hours per year the ORU under analysis is in operation. Most ORUs are assumed to be continuously operating; therefore, the default value is 8760 hours per year.

Dictated Probability. This parameter is the required probability of mission success. This parameter is related to the criticality factor of the ORU under analysis (14:D109). For example, criticality 1 items are assigned a dictated probability of .99. Criticality 2 items are assigned a value of .95, and criticality 3 items .90. The

criticality factor of an ORU is provided by the system analyst at KSC, and relates to the relative importance of the specific ORU's functioning during Space Station operations (27). Generally, the higher the dictated probability of success, the higher the number of spares required for support (27).

ORU Turnaround Time. This is the time required to repair and refurbish a failed ORU after it returns from the Space Station. The total duration of turnaround time depends on the maintenance action required, the travel time from KSC to the manufacturer, and processing time (27).

Years of Operation. This is the total projected length of time in years the Space Station is to be operational. The default value is 30 years.

All these input parameters are critical to the spare calculations. The user is responsible for the accuracy of these values. When prompted by the program, the user simply inputs these parameters and Keyspares calculates the required spares.

Model Calculations

As stated, Keyspares estimates required lifetime spares in a two-stage calculation.

Failure Generation. The first stage of the calculation is to generate the number of failures an ORU will experience during its operational lifetime. The

number of failures is generated by a Poisson summation process:

$$P(x) = \sum_{x} \left[\frac{\beta^{x} e^{(-\beta)}}{x!} \right] \tag{7}$$

where:

β = KT/MTBF

K = number of ORUs installed

T = average annual operating hours * years of operation.

P(x) = the dictated probability of success as generated by the ORUs criticality factor

X = summation index (number of failures)

This simple Poisson probability is summed until it is greater than or equal to the dictated probability $\{\sum p(x) >= P(x)\}$.

This resultant sum is called the assessed probability. For example, one failure is generated and this failure is expressed as X. Then the calculated or assessed probability is compared to the dictated probability P(x). If the assessed probability is lower than P(x), the process is repeated and summed with all prior calculations. When the assessed probability is equal to or greater than the dictated probability, the process is ended. The final summation index value X represents the number of ORU failures generated over the Space Station's operational lifetime.

Equation Sensitivity. There are two parameters whose values may cause problems in this equation. They are ORU quantity installed and ORU MTBF. If an ORU has a large installed population and a low design MTBF, the resulting generated failures may exceed the capabilities of a standard personal computer. If this situation occurs, Keyspares writes an error statement and asks the user to re-input parameter values. According to the Keyspares user manual, the limits for these parameters are:

1. At least 50,000 hours for design MTBF.
2. Less than 25 installed ORUs.

These two limits can not be realized at the same time or a computer math overflow will occur (14:D112).

Spares Calculations. The second stage of the Keyspares program is the spares calculation. Spares are calculated using the following simple FORTRAN-based mathematical algorithm.

```
K = 8 * Y                                 (8.1)
A = X / K                                 (8.2)
B = TAT1/CTIME                            (8.3)
I = B                                     (8.4)
C = B - I                                 (8.5)
IF (C .GT. P) I = I + 1                   (8.6)
D = I * A                                 (8.7)
J = D                                     (8.8)
E = D - J                                 (8.9)
IF (E .GT. 0) J = J + 1                   (8.10)
```

Where

Y = years of Space Station operation

X = number of failures generated

TAT1 = ORU turnaround time

CTIME = ORU resupply cycle time

J = spares

C,E = rounding variables

Spare Calculation Objective. This mathematical algorithm has three main objectives.

The first objective is to determine the number of failures an ORU will have per total number of lifetime resupply cycles. Equation 8.1 represents the total number of program lifetime resupply cycles. Where the constant 8 represents an assumed 45 day resupply cycle (45 day cycle = 8 cycles per year) times Y years of Space Station operation. Equation 8.2 translates the number of generated failures into failures per resupply cycle (27). For example, if 50 ORU failures occur in 30 years of Space Station operation with an assumed 45 day resupply cycle, then the failures per cycle are equal to [50/(8 * 30) = 0.2] failures per resupply cycle.

The second objective is to determine the time a repaired ORU will be unavailable or be in the repair pipeline. Equation 8.3 calculates this value. For example, with an ORU turnaround time (TAT1) of 350 days and a scheduled orbiter resupply of every 90 days (CTIME), the failed ORU will be in the repair pipeline for 350 / 90 =

3.88 resupply cycles. This calculation represents the number of resupply cycles in which spares need to be on-hand to provide adequate ORU support. Since resupply cycles are a discrete value, equations 8.4 through 8.6 ensure that the next highest whole integer represents the unavailable resupply cycles.

The third objective of this calculation is to determine the number of spares required. Equation 8.7 multiplies the number of failures per resupply cycle by the number of cycles the ORU will be unavailable. For this example, the calculated 0.2 failures per program resupply cycle are multiplied by the 4 cycles in which the ORU is unavailable due to repairs. Thus 0.2 * 4 = 0.8 spares are required to support this time interval. Once again, the number of spares must be a whole integer, so round the estimate to the next highest whole integer. This process is done in equations 8.8 through 8.10.

Model Output. The Keyspares program provides two types of model outputs: the normal and the alternative outputs. The normal output presents results of output parameters when normal calculations do not exceed mathematical limits. When these limits are exceeded, the alternate format is produced. Both of these outputs present all input parameters except ORU turnaround time, as well as the number of failures generated and spares required. Please refer to Appendix A: Keyspares User Manual for a display of screen outputs.

Model Assumptions

The Keyspares model assumes that the component failure (hazard) rate is constant over the useful life of the Space Station, thereby also assuming ORU failures can be represented by an exponential distribution. According to Werpy, this is a valid assumption for the following reasons (27).

1. All ORUs undergo extensive testing and "burn-in" prior to being released for service on the Space Station. This initial testing screens faulty ORUs that may fail in a manner characteristic of infant mortality.

2. Due to what Werpy calls "reasonable technology," the design and function of the ORUs are well known (27). Most of the Space Stations' ORUs do not represent new technology, but rather new applications of current technology. The function and failure characteristics of these ORUs are well known, analyzed, and documented (27).

The Keyspares does not account for spares to replace the following types of failures.

1. Infant Mortality. These are failures early in the life of an ORU.

2. Test Failures. Failures due to stress invoked during the test of components.

3. Assembly and Check-Out Failures. Failures due to maintenance errors during system check-out and analysis.

Another major assumption of Keyspares is that it does not account for dependent or cascading failures. Keyspares assumes that component failures are independent of one another. That is, if one component fails, its failure will not cause another component to fail (14:D113).

Literature Review Summary

This chapter presented the problems of supply support the Space Station will experience. First, a review of the design and environmental constraints of space-based systems was presented, also a review on how these constraints can affect supply support was conducted. Next, a review of support techniques found in the literature that can account for system constraints was presented, along with a review of support techniques for past space systems. Then an in-depth review of reliability theory and how a components' failure characteristics influence spare requirements was shown. Next, a review of the use of simulation in inventory modeling shows its usefulness as a support analysis technique. Finally, an in-depth review of the Keyspares sparing model is given, showing how initial spares are calculated for the Space Station, as well as the key assumptions that underlie the Keyspares model.

Chapter III presents the methodology used to evaluate the Keyspares model and its assumptions.

III. Methodology

Chapter Overview

The purpose of this chapter is to describe the procedures used to evaluate the Keyspares sparing model. In this chapter, each specific research objective presented in Chapter I is restated, followed by a detailed description of the methodology used to address these objectives.

Keyspares Model Evaluation

Objective. Present a thorough discussion of the Keyspares model, including the assumptions which it incorporates and the results that are obtained when the model is run.

Method. Three primary methods were used to address this objective.

1. Telephone interviews with Mr. Jim Werpy, the creator of the Keyspares sparing model.

2. Telephone interviews and correspondence with users of the Keyspares model at the Kennedy Space Center (KSC).

3. Running the Keyspares model for the Space Station's EPU system for both 30 and 50 years of Space Station operation.

To gain a thorough understanding on the functioning of the Keyspares model, telephone interviews with logistic personnel at KSC and Mr. Jim Werpy of Boeing Corporation

were conducted. Each interview focused on these important questions:

1. What is Keyspares?

2. What is its function?

3. How does it calculate spares, and what is the usefulness of these calculations?

4. What are the model's assumptions, and how do they affect the interpretation of the spare calculations?

The findings from these interviews are presented in the discussion of the Keyspares model found in Chapter II. Another source of information was the Keyspares user manual, written by Mr. Jim Werpy under contract for NASA. The Keyspares user manual is presented in Appendix A.

To evaluate the model, Kennedy Space Center employed Keyspares to compute the sparing requirements for the Space Station's Electrical Power Unit (EPU) system. The Keyspares model was ran for both a 30-year and a 50-year proposed life-span of the Space Station.

Model Inputs. To successfully run the Keyspares model specific input parameters are required. They are ORU quantity per platform, design mean time between failure and the designated repair center to determine repair turnaround times. Finally, the model makes several specific assumptions.

1. A 90-day resupply cycle. The Space Station would be continually resupplied without delay every 90 days.

2. For all items the dictated probability of an ORU successfully functioning was 0.95, or a criticality assessment factor of 2.

3. Two model runs were evaluated: one 30-year run, and one 50-year run, each representing a proposed life-span for the Space Station.

4. The repair turnaround time depended on where the ORU was repaired. Two primary locations were used to determine the repair turnaround time. First, if the ORU was repaired at KSC, its repair turnaround time was 60 days. Second, if the ORU was repaired by a contract vendor, its repair turnaround time was assumed to be 105 days. All the assumptions and ORUs used in this test run were provided by KSC, as were the results of ORU failures and required spares.

Table 1 shows the ORUs that make up the EPU system and its input parameters (13).

System Background. The Space Station system used in this Keyspares evaluation is the Electrical Power Unit (EPU) system. This system is a critical on-board system that consists of 25 ORU components. The EPU system controls the electrical power requirements for the on-board living quarters and work areas (15). This system was chosen for two reasons.

1. This system is representative of an on-board critical system. The failure of this system will shut

Table I.

Keyspares input parameters for the Space Station's EPU system.

ORU NAME	QPA	MTBF	REPAIR CENTER
Power Conversion Unit	2	175200	KSC
Engine Controller	2	87600	Vendor
Concentrator Controller	2	265400	Vendor
Photovoltaic Contr. Unit	2	265400	Vendor
Photovoltaic Controller	2	43800	Vendor
Power Source Processor	2	43800	Vendor
Frequency Converter	2	265400	Vendor
Solar Dynamic Controller	2	43800	Vendor
Power Mgmt. Processor	2	43800	Vendor
Linear Actuator U-Joint	4	57000	Vendor
Beta Joint Controller	4	87600	Vendor
AC/DC Converter I&C	4	256400	Vendor
AC/DC Converter Motor	4	265400	Vendor
DC/AC Inverter	4	175200	Vendor
Main Bus Swch. Unit	4	87600	Vendor
Beta Drive Motor	6	87600	KSC
Linear Actuator Cont.	8	87600	Vendor
Battery Charger/Disch.	8	87600	Vendor
Transformer	8	87600	Vendor
Pressurization Unit	16	175200	Vendor
Radiator Panels	22	175200	Vendor
Power Discharge Cont.(IVA)	22	43800	Vendor
Power Discharge Cont.(EVA)	24	43800	Vendor
Battery Assy. NiH2	32	61320	Vendor
Radiator Panel (AFT)	64	175200	KSC

Abbreviation Key:

QPA = Quantity installed on-orbit

MTBF = Design mean time between failure in hours

Repair = Repair center. Vendor = Vendor repair, KSC = KSC repair.

down Space Station operations until required maintenance is performed.

2. This is a mature system. The design is well known and stable. This system's sub-components have verified reliability and maintenance parameters, and on-board quantities. Finally, this system has been used extensively in Space Station logistical studies, as well as in the development of the Keyspares sparing model (15).

Model Output. The Keyspares model presents two primary outputs. First, using the general reliability equation, Keyspares determines the number of failures an ORU will experience during the projected lifetime of the Space Station. Second, using the number of failures generated, Keyspares uses an algorithm to determine the number of spares required to support the ORU during its operational lifetime. The results and analysis of the Keyspares simulation runs are presented in Chapter IV.

Theoretical Literature

Objective. Locate, analyze and discuss the theoretical literature that either supports or refutes the Keyspares assumptions.

Method. The methods used to evaluate this research objective were as follows:

1. Conduct an in-depth review of the literature. This review started with the theoretical literature on reliability and how reliability theory is used to determine

failure rates of components. Also, a review of failure distributions was conducted. This review analyzed failure distribution assumptions and how they can be used to describe component failure characteristics.

2. Telephone interviews with users of Keyspares at KSC and its creator, Mr. Jim Werpy, provided much of the information concerning model assumptions. These interviews also highlighted reasons why these assumptions were made, and the importance of these assumptions to the Keyspares model outputs. The results of these interviews and the theoretical literature review were presented in Chapter II.

Space Station's Spare Requirements Simulation

Overview. To effectively evaluate the Keyspares sparing model, a comparison was made to a simulation of the Space Station's ORU demand requirements and resupply environment. This simulation generated EPU ORU failures over a 50 year lifespan of the Space Station. In addition to generating ORU failures, this simulation modeled the resupply pipeline a failed ORU would traverse during its operational lifetime.

Objective. Produce a simulation of the Space Station's resupply pipeline using selected EPU ORU components.

Method. "In order to resolve problems using simulation models, it is necessary to understand the system under study and define problems relating to that system" (18:3). This methodology follows Pritsker's approach by

modeling the resupply and demand generation of the Space Station's EPU ORUs. In simulating the resupply pipeline of the Space Station, the Simulated Language of Alternative Modeling or SLAM II simulation language was used. SLAM II is an advanced FORTRAN-based simulation language that allows models of real-world systems to be analyzed and evaluated. The SLAM II simulation language was created by A. Alan B. Pritsker.

Simulation Development

The objective of the simulation was to accurately describe the ORU failure and resupply process of the Space Stations' EPU system. In order to model this system, specific parameters were required. The Space Station's logistical managers, working out of KSC, provided all of the necessary EPU ORU and resupply parameters used in this simulation. The parameters they provided are as follows:

EPU Components. This is a listing of sub-components that make up the Space Station's EPU system. Parameters provided were the ORU names, quantity installed per system, the design MTBF, the repair center where the ORU is maintained, and the repair turnaround time. Table I gives a complete list of all the EPU components and their input parameters.

Resupply Cycle. This parameter is the time between resupply missions to the Space Station. It is assumed that the Space Shuttle will be the primary resupply vehicle used to resupply the Space Station. Also, it is estimated that a

minimum of four resupply missions per year will be scheduled to resupply the Space Station (17). For this simulation, four resupply missions are assumed to be scheduled in exactly 90 day intervals with no interruption.

EPU ORU Selection. Three EPU ORUs were selected for investigation. The criterion used for component selection was to select ORUs that were representative of critical on-board components. Each component was to have various levels of on-board installed ORUs, as well as design MTBF low enough so that enough data would be generated for the 50 year simulation. The three EPU ORUs selected, and their input parameters are:

ORU NAME	QPA	MTBF	REPAIR CENTER
Engine Controller	2	87600	Vendor
Linear Act. U-Joint	4	57000	Vendor
Transformer	8	87600	Vendor

Simulation Model

Figure 4 shows the simulation network used to describe the failure and resupply of the EPU components under study.

This simulation uses the SLAM II symbology to describe system events; this SLAM II symbology is explained in Appendix C. One note is necessary to assist the reader in understanding the network model in Figure 4. The SLAM II model spans three pages, and connectors are provided to enable the reader to trace the network from page to page without loss of direction. These connectors, which appear as large letters, serve only as guides to the reader and not

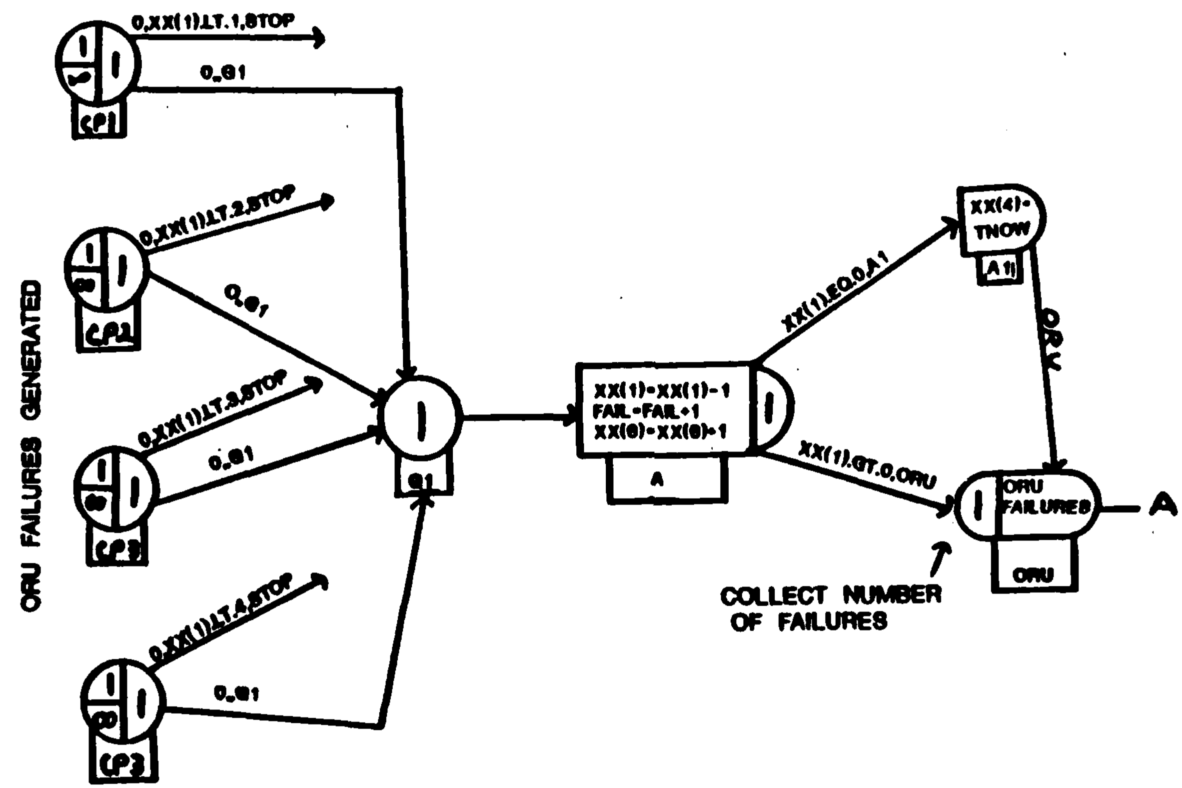


Figure 4. A SLAM II Network of ORU Resupply

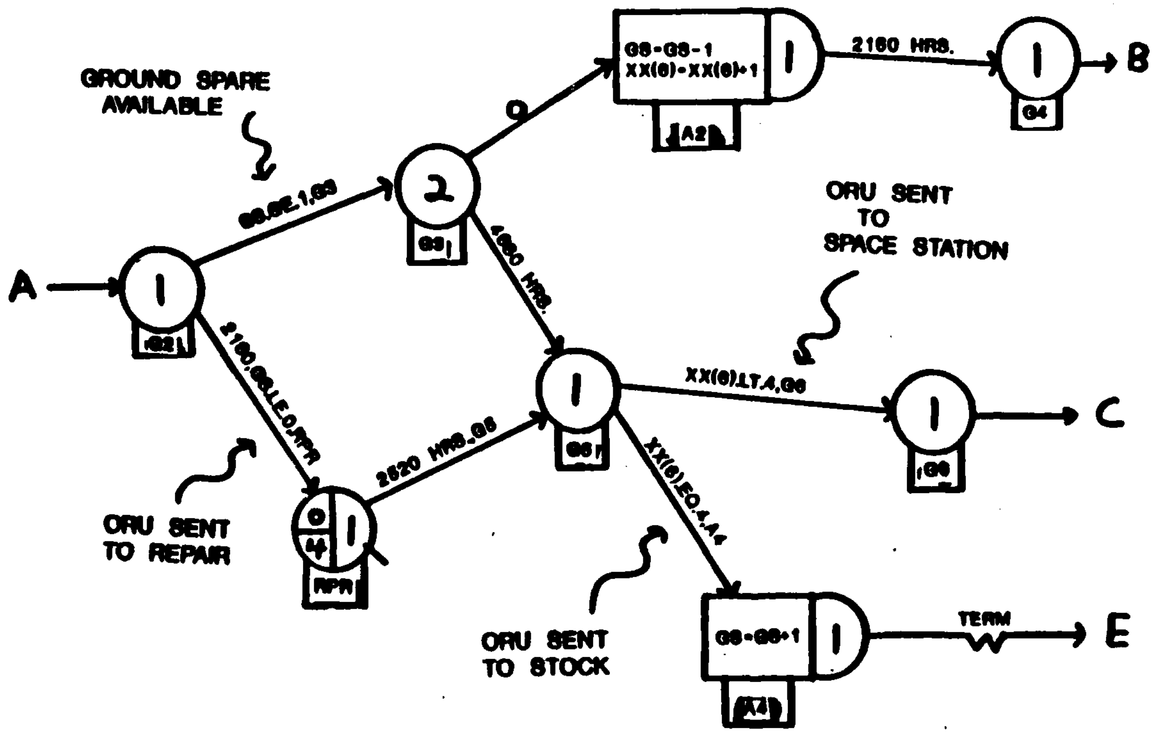


Figure 4. (continued)

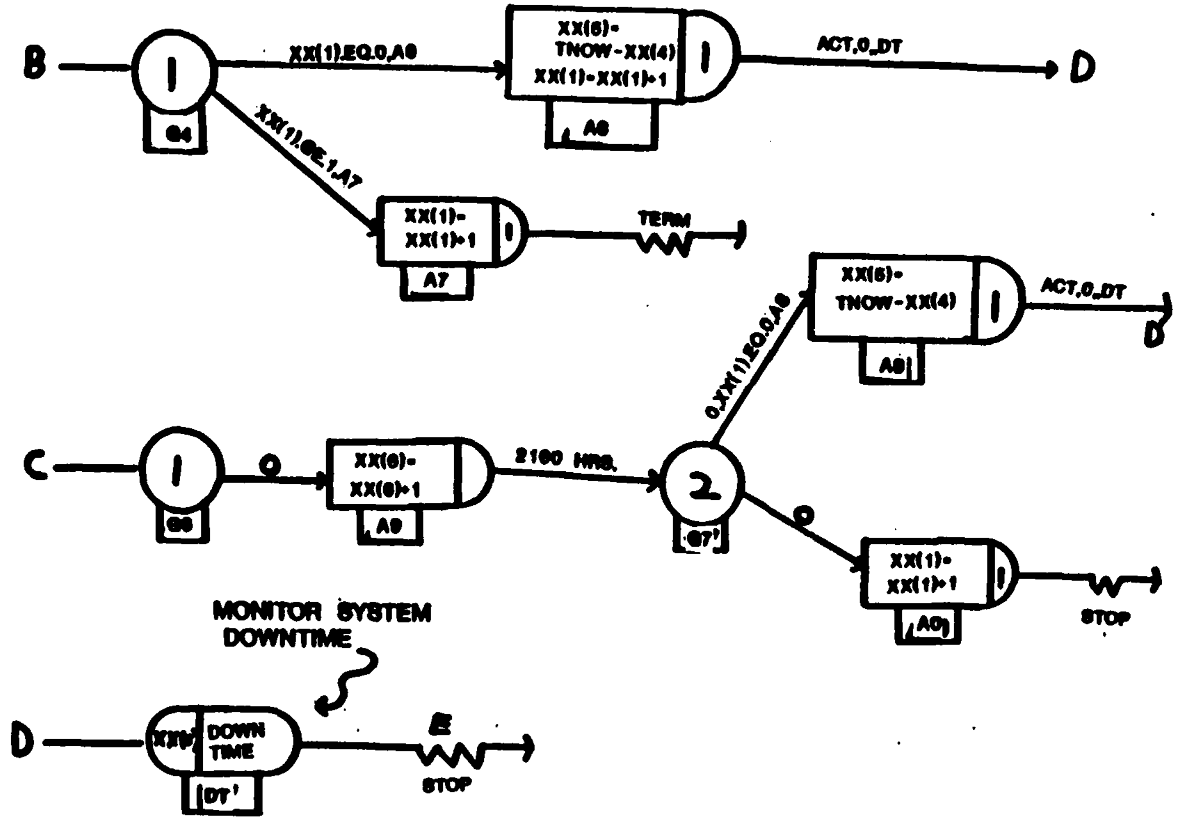


Figure 4. (continued)

as activity nodes in the network. The computer code for each simulation is presented in Appendix D.

System Analysis

This simulation of the Space Station's EPU resupply system can be broken down into three main segments.

1. Generation of on-board failures of EPU components
2. Repair and resupply of on-board failures
3. Statistical monitoring of key variables of interest

Failure Generation. The first segment, component failure generation, is accomplished by SLAM II create nodes identified by labels CP1 through CP4 respectively. These nodes generate entities (failures) at a user specified rate. In Figure 4, the Linear Actuator U-Joint is used as an example. This EPU ORU has a design MTBF of 57000 hours, with a total of four ORUs installed on-board the Space Station. The SLAM II create node uses information to simulate a component failure by randomly selecting a failure event from an exponential distribution with mean time between failure of 57000 hours. After a failure entity is created, it moves along the network and triggers value assignments of key variables of interest. For example, after node G1 the variable installed quantity (XX(1)), originally set at four, is reduced by one, the variable failure (XX(2)) is increased by one, and the ORU decision variable (XX(6)) is reduced by one.

Repair and Resupply Activities. The second segment of the simulation is the repair and resupply of a failed EPU component. In this simulation model, all failed ORUs must return to earth for repair, and then either return back to the Space Station to replace a failed ORU or remain on earth as a spare. In this simulation, a worse case resupply scenario is used. That is, every time an ORU fails the model assumes it will take 90 days until it is sent to earth for repair. This 90 day transit time represents the longest possible time between planned resupply missions. Once the ORU is repaired, processed, and available for resupply, it is assumed that it will take 90 days for the ORU to be transferred to the Space Station.

Resupply Decision. Throughout the simulation network there are instances where a decision is required as to how resupply of the failed ORU is to be accomplished. Basically, there are two possible resupply decisions.

1. Use a ground spare to resupply the failed ORU if it is available, or

2. Wait for a repaired component from the repair pipeline.

In both of these resupply decisions, the availability of a ground spare is the driving factor. The Keyspares sparing model has recommended one required spare for each of the EPU components under study. The simulation uses this fact, and has assigned one ground spare to each simulation run.

At this point a walk through of the decision process will be useful to the reader.

Simulation Example. First, an EPU component failure is generated. As this failure proceeds through the simulation, it reduces the operational installed quantities by one. Since it is assumed that only one on-board ORU is necessary for the EPU system to remain operational (27), no system shut-down will occur unless all four on-board components are inoperable at the same time.

When the failed ORU reaches decision node G2, the availability of a ground spare is monitored. If a ground spare exists, two activities will occur. First, the ground spare is sent to the Space Station to replace the failed ORU (node G3), and the operational installed quantity (represented by XX(6)) is increased by one (90 days later). Second, the failed ORU is sent to earth for repair. When the repaired ORU comes out of repair, a decision on its status is made (node G5). The installed ORUs are monitored; if one is inoperable (failed), the repaired ORU is sent to replace it (node G6). If there are no failed ORUs, then the repaired ORU is sent to stock as a ground spare (node A4).

If at decision node G2, a ground spare does not exist, then the failed ORU is sent to an earth repair facility (node RPR). When the ORU comes out of repair, the same decisions are made as to its status. If no on-board failures are evident, the ORU is sent to stock as a ground

spare. If an on-board failure exists, then the repaired ORU is sent to the Space Station to "fill the hole."

Statistical Monitoring. The third segment of this simulation is the statistical monitoring of key system variables. In order to effectively evaluate the Keyspares sparing algorithm, critical system events need to be analyzed. This simulation monitors the following system variables:

1. Installed ORU quantity. The installed ORU quantity was monitored to analyze the percentage of time ORUs were operational. This statistic was monitored by a time persistent SLAM II command. Please refer to Appendix C.

2. System down-time. This statistic measured the time the EPU system was down because all installed ORUs were inoperable at the same time. This statistic is collected at node DT (D) in the SLAM II network model.

3. The percentage of time ground spares were in use. This statistic provides inferences as to how long calculated spares were in use. This statistic is also monitored by a time persistent SLAM II command.

4. The number of ORU failures. This statistic is used as a comparison to the Keyspares failure predictions for a 50-year lifespan of the Space Station.

Model Validation

Validation is the determination that a model is an accurate representation of the real system (18:13). In the

case of the resupply system for the Space Station, this determination is particularly difficult since the Space Station is not actually functioning but is currently only a system concept. However, this study attempted to validate the resupply system with respect to its function and logic. The validation process used in this simulation consisted of two techniques.

1. A graphical representation of the EPU ORU failure and resupply process was modeled. Analysis shows the model's behavior and output over time are consistent with previous outcomes predicted by the Keyspares model. For example, failures did not occur frequently, as expected with a high design MTBF and relatively low installed quantities. Also, output quantities, such as the number of failures, were consistent with Keyspares' estimates.

2. The method of expert opinion was used to evaluate the model's validity. All of the necessary resupply events and input parameters were described by logistical personal working on the Space Station program at KSC, a high degree of confidence is felt that the simulation accurately models the proposed Space Station's resupply system. In validating the SLAM II computer code and resupply logic, Lt. Col. Schuppe, Dr. Fenno and Capt. Peterson of the Air Force Institute of Technology provided much insight and direction in evaluating the simulation.

Simulation Comparison To Keyspares

Overview. One of the key assumptions of the Keyspares sparing model is that the component failure (hazard) rate is constant over the useful life of the Space Station. Thus, it is assumed ORU failures can be represented by an exponential distribution. To test the validity of this assumption, selected EPU components were simulated over a 50-year simulation employing the Keyspare assumption of exponential failure rate of EPU ORUs.

Objective. Run the developed simulation, using Keyspares' assumptions, and compare the results of the simulation with results of the Keyspares model.

Method. To meet this research objective, a simulation of the three selected EPU ORUs was performed using the assumptions from the Keyspares model. The Keyspare assumptions employed in this simulation are as follows:

1. Each ORU's failure rate was assumed to be exponentially distributed.

2. The simulation was ran for 50 years, representing the estimated operational life of the Space Station.

3. Since the Keyspares model predicted only one spare for each EPU ORU, only one spare per simulated ORU was assigned.

4. All MTBF's are distributed exponentially.

A summary of the simulation input parameters follows:

ORU NAME	QPA	MTBF	SPARE	REPAIR TURN-TIME
Engine Controller	2	87600	1	105 days
Linear Act. U-Joint	4	57000	1	105 days
Transformer	8	87600	1	105 days

Performance Measures

To compare the results of the simulation with the results of the Keyspares' model, the following performance measures were used:

1. Total number of generated failures. This is the total number of failures that were experienced by an ORU during a 50-year simulation. Note that the total number of failures represents an aggregate lifetime failures for all ORUs installed on the Space Station.

2. A key requirement of the Keyspares model is that each EPU component has a criticality factor of 2. That is, each ORU must be operational 95% of the time. In order to satisfy this requirement, at least one ORU must be operational for 95% of the Space Station's lifetime. To evaluate this Keyspares' requirement, the number of operational ORUs and the percent of time each installed ORU was operational were analyzed. As an example, if the simulation showed that at least one ORU was operational 95% of the time, an inference could be made that the spare calculation provided by the Keyspares model was adequate to meet this requirement.

3. System down-time. Another performance measure of interest is the total system down-time. Since the goal of a

successful Space Station is to be continuously operational, a key management measure is to know if a failure of a system will cause the Space Station to be inoperable and, if so, for how long?

4. Spare ORU utilization. A measure of interest is to know the percentage of time the sole ORU spare was in use. A high utilization percentage may imply an inadequate sparing policy, while a low utilization percentage may imply that Keyspares adequately estimated the number of spares.

Output Analysis

One of the main problems in employing a simulation is ensuring the output accurately reflects the system under study (18:115). In order to minimize any problems in output data, the following techniques were used:

1. To ensure internal consistency of failure generation, each simulated ORU had a designated random number stream. Simulated ORUs maintained their assigned random number stream throughout each simulation run.

2. Since each EPU ORU had a relatively high MTBF, a failure of an ORU was considered a "rare event." This situation posed many problems in interpreting when and if system steady-state was achieved. To minimize this problem, each simulation was ran for 1000 years with statistics reported and cleared every 50 years. This provided 20 batches of 50 year simulations to observe and analyze. By

analyzing 20 batches of data rather than one, the following benefits were realized. First, the additional data provides a better estimate of events during system steady-state. Second, since each random number stream uses a different generating seed at each replication, the output statistics are independent from random number stream bias. Finally, the performance measures output are averaged over the 20 batch runs. This provides protection against a "rare occurrence" that may be found if only a single run was analyzed.

Variation of Keyspares Failure Assumption

Overview. An important objective of this study is to evaluate the Keyspares sparing model when the ORU failure rate assumption is altered. By varying the exponential failure rate assumption of EPU components, an evaluation of the adequacy of the Keyspares model may be attempted.

Objective. Run the simulation while varying the failure rate distribution of EPU ORUs, and determine the differences resulting from each variation.

Method. To evaluate the Keyspares' sparing model under different failure rate distributions, the following methods were used.

1. A simulation was performed using the normal distribution as the failure (hazard) rate distribution.

2. A simulation was performed using the Weibull distribution as the failure (hazard) rate distribution.

Normal Distribution Simulations. In these simulations, the normal distribution was used to represent an increasing component failure rate over time, as characterized by the component "wearout" region of the classical bathtub curve. In each simulation, the SLAM II create nodes for each ORU were altered to reflect a normally distributed MTBF. The same performance measures and output analysis was performed as in the simulations of ORU failures under the exponential failure distribution.

Sensitivity Analysis. Under the normal distribution, the mean and standard deviation are the two parameters that determine the distribution's shape. The design MTBF, provided by KSC, was used to represent the mean failure rate. Since no data was available to estimate the standard deviation of mean failures, a sensitivity analysis was conducted. For each simulation, three levels of standard deviations were used and analyzed. They were

1. The standard deviation of mean failures was set at 15% of the design MTBF.

2. The standard deviation of mean failures was set at 10% of the design MTBF.

3. The standard deviation of mean failures was set at 5% of the design MTBF.

As a general observation, the smaller the standard deviation, the higher the confidence in the design MTBF, and the more predictable the mean failure rate.

Weibull Distribution Simulations. In these simulations, the Weibull distribution was used to represent a decreasing ORU failure rate, characteristic of the "infant mortality" region of the bathtub curve. As in previous simulations, the same performance measures were analyzed. Also, parameter output analysis was performed.

Weibull Sensitivity Analysis. Much like the normal distribution, two parameters are required to determine the shape of the Weibull distribution, the mean and the shape parameter. For all Weibull simulations, the design MTBF's of the selected EPU components were used. Since the Weibull distribution was chosen to represent a decreasing component failure rate, the shape parameter (s) must be less than one. Three levels of s were used to evaluate the sensitivity of output statistics. They were

1. The shape parameter was set at 0.7, representing a gradually decreasing failure rate.

2. The shape parameter was set at 0.5, representing a moderately decreasing failure rate.

3. The shape parameter was set at 0.3, representing an extremely quick decreasing failure rate.

Chapter Summary

This chapter presented the methodology used to evaluate the Keyspares sparing model. Each research objective was presented, followed by a description of the methods used to

address the stated objective. A description of the simulation model developed was presented, followed by a description of the performance measures used to analyze and evaluate the efficacy of the Keyspares model. Chapter IV presents an analysis of the these simulations and any findings that warrant comments.

IV. Results and Analysis

Introduction

This chapter presents the results of the simulations developed to evaluate the Keyspares sparing model and to draw conclusions about Keyspares' effectiveness as an ORU sparing model. The overall objective of this analysis was twofold. The first objective was to evaluate the Keyspares model under its intrinsic assumption of a constant ORU failure rate. To accomplish this objective, an analysis of the simulation with an exponential ORU failure rate was compared to the results of failures and spare requirements generated from the Keyspares model. The second objective was to evaluate the Keyspares model while varying the ORU failure rate assumption. To accomplish this objective, an analysis of two simulations was conducted. One simulation was conducted using the normal distribution to represent an increasing ORU failure rate, another simulation was evaluated using the Weibull distribution to represent a decreasing ORU failure rate.

In each of these simulations specific statistics were analyzed to draw inferences on the effectiveness of the Keyspares sparing model. The statistics analyzed were:

1. Average number of generated failures. This statistic represents the average number of ORU failures generated during 50-years of simulated Space Station

generated during 50-years of simulated Space Station operation.

2. The percent of time an installed ORU was operational. For each simulation, the average time an on-board ORU was operational was monitored. According to the Keyspares ORU criticality assumption, at least one ORU is required to be operational 95% of the time. Monitoring this statistic provided a means to evaluate the effectiveness of the Keyspares model in satisfying this critical condition.

3. System down-time. This statistic monitored the total time the EPU system was inoperable. Because the EPU system is a critical on-board system (17), when the EPU system is inoperable the entire Space Station is rendered inoperable.

4. The percent time a spare was in use. Each simulation was assigned a single ORU spare as estimated by the Keyspares Sparing algorithm. During the simulation, the percentage of time the ORU spare was in use was monitored. If the spare quantity was zero, then this represented an "in-use" spare (transit and repair pipeline time). If the spare quantity was equal to one, then this represented an "on-the-shelf" spare.

Chapter Overview

The results of the research are presented, beginning with the Keyspares' stockage recommendations for EPU ORUs.

The number of failures and calculated spare ORU levels are presented for a 30-year and 50-year time period. Second, a comparison of the simulation results under a constant ORU failure rate are contrasted to the Keyspares results. Third, the results of the simulations under an increasing ORU failure rate are contrasted to the results of the Keyspares results. Finally, the results of the simulations under a decreasing failure rate are contrasted to the Keyspares results.

Keyspares Results

The Space Station logistical personnel, working out of KSC, used the Keyspares model to evaluate all EPU ORUs. This evaluation provided the recommended spares stockage to maintain the EPU system operational for the proposed lifetime of the Space Station. Their analysis was conducted for a 30-year and 50-year Space Station lifetime. Table II presents the results of their evaluation.

The ORU failures computed by the Keyspares model assumes a constant failure rate. As shown in Table II, two trends are apparent.

1. When the number of on-board ORUs increases, the number of lifetime ORU failures increases. This relationship is obvious since with a greater population of on-board ORUs, the greater the percentage of operational

Table II.

Keyspares Evaluation of the EPU System

ORU NAME	QPA	MTBF	30-YEAR FAIL.	30-YEAR SPR.	50-YEAR FAIL.	50-YEAR SPR.
Power Conversion Unit	2	175200	6	1	9	1
Engine Controller	2	87600	10	1	14	1
Concentrator Controller	2	265400	5	1	7	1
Photovoltaic Contr. Unit	2	265400	5	1	7	1
Photovoltaic Controller	2	43800	18	1	26	1
Power Source Processor	2	43800	18	1	26	1
Frequency Converter	2	265400	5	1	7	1
Solar Dynamic Controller	2	43800	18	1	26	1
Power Mgmt. Processor	2	43800	18	1	26	1
Linear Actuator U-Joint	4	57000	26	1	37	1
Beta Joint Controller	4	87600	18	1	25	1
AC/DC Converter I&C	4	256400	7	1	10	1
AC/DC Converter Motor	4	265400	7	1	10	1
DC/AC Inverter	4	175200	10	1	14	1
Main Bus Swch. Unit	4	87600	32	1	42	1
Beta Drive Motor	6	87600	25	1	35	1
Linear Actuator Cont.	8	87600	32	1	45	1
Battery Charger/Disch.	8	87600	32	1	45	1
Transformer	8	87600	32	1	43	1
Pressurization Unit	16	175200	32	1	45	1
Radiator Panels	22	175200	43	1	63	1
Power Discharge Cont.(IVA)	22	43800	MO	MO	MO	MO
Power Discharge Cont.(EVA)	24	43800	MO	MO	MO	MO
Battery Assy. NiH2	32	61320	MO	MO	MO	MO
Radiator Panel (AFT)	64	175200	112	1	157	2

MO = Mathematical Overflow, no output was created.
FAIL = The number of failures observed.
SPR. = The number of spares recommended by Keyspares.

ORUs. With a greater proportion of operational ORUs, the probability that at least one will fail is higher.

2. The second trend observed is that as an ORU's MTBF increases, the fewer the total number of ORU failures generated.

One criticism of the Keyspares model is that it fails to compute stock levels for ORUs with a low MTBF and a high number of on-board ORUs. This is demonstrated in the Power Discharger Controller ORU, where the design MTBF is a relatively low 43800 hours and the on-board quantity is greater than 20. This presents a limiting factor on the ability of the Keyspares model to effectively evaluate the number of spares required for Space Station systems. Finally, the algorithm used to determine spares appears to be relatively insensitive to the number of failures generated. For example, for all EPU ORUs, except Radiator Panels (AFT), only one spare was calculated. The Radiator Panels (AFT) required two spares for lifetime support, but this ORU had an extremely high number of on-board ORUs at 64. It is apparent the Keyspares sparing algorithm only recommends more than one spare when the number of generated ORU failures is extremely high.

Exponential Failure Rate Simulations

To evaluate the results of the Keyspares sparing model, a simulation of the Space Station's EPU system was conducted employing the constant ORU failure rate

assumption. To represent the constant ORU failure (hazard) rate, the exponential distribution was used to generate on-board ORU failures. Figure 5 presents a comparison of the number of ORU failures generated by the Keyspares model versus the simulations. As shown in Figure 5, the number of failures increases as the number of installed on-board quantities increase. Also, for all ORUs, the number of ORU failures computed by the Keyspares model is consistently higher than ORU failures generated by the simulation. One explanation for this difference is an assumption used in developing the simulation. For each simulated ORU two conditions existed. If the ORU was operational, then ORU failures could occur; however, if the ORU had failed it's operational clock was shut down until it was removed, repaired and or replaced. Therefore, the MTBF parameters were only relevant when an ORU was operational. This condition was not accounted for by the Keyspares sparing model, where failures were calculated based on the design MTBF without regard to monitoring whether the ORU was operational or not. By employing this condition, fewer failures occurred for the simulation models than predicted by Keyspares.

Table III presents the statistics collected for the simulations under a constant ORU failure assumption.

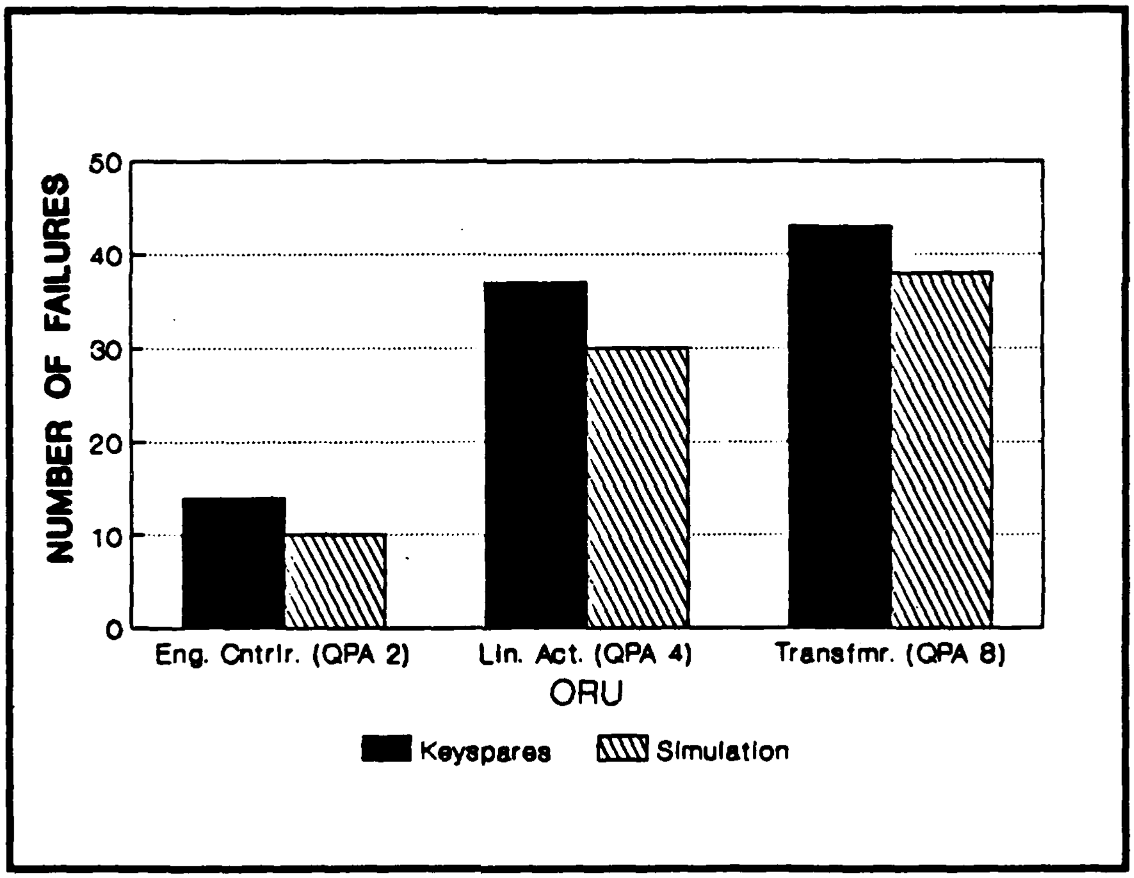


Figure 5. Number of ORU Failures (Exponential Hazard Rate)

Table III. Simulation Statistics (Exponential Hazard Rate)

ORU	Avg. Downtime	% Time ORU Operational									% Time Spare Used	
Qty.		0	1	2	3	4	5	6	7	8	0	1
Eng. Cntrlr.	285	.1	4.9	95	-	-	-	-	-	-	10	90
Lin. Act.	0	0	.1	.90	13	86	-	-	-	-	28	72
Transfrmr.	0	0	0	0	0	0	.2	2	17	81	35	65

As shown in Table III, the Engine Controller averaged 285 hours of system downtime for a 50-year operational lifetime. This relates to an average Space Station downtime (due to the EPU system) of 12 days during every simulated 50-years of operation. Table III also shows that on average, .1% of the time none of the installed Engine Controllers were operational. Finally, the single Engine Controller spare was in the repair pipeline 10% of the time. In contrast to these results, no downtime was observed for the Linear Actuator U-Joint or Transformer ORUs. The downtime observed would result in a complete shut-down of the EPU system, impacting the ability of the Space Station to be safely manned. The detailed simulation output statistics are presented in Appendix E.

Normal Failure Rate Simulations

In these simulations the ORU failure rate was assumed to be normally distributed, representing an increasing ORU

failure rate over time. The detailed results of these simulations are also presented in Appendix E.

Figure 6 compares the number of failures computed by the Keyspares model against the normally distributed failures generated in the simulation. For these simulations, three estimates of standard deviation were used to check the sensitivity of ORU failure generation variance. The three standard deviation levels were 5, 10 and 15% of MTBF.

As shown in Figure 6, the number of ORU failures computed by Keyspares were consistently greater than failures generated by the simulations. Also, there appeared to be no significant difference in the number of failures generated over the three standard deviation levels of the MTBF.

Table IV presents the percent time a spare was available, percent time an ORU was operational at a given time, and downtime statistics for the simulations under a normally distributed ORU failure rate assumption.

As Table IV shows, the ORU Engine Controller with two on-board ORUs experienced Space Station downtime across all three standard deviation levels. The highest average downtime was observed at a 5% MTBF standard deviation with a mean system downtime of 245 hours. The percent of time a spare ORU spent in the repair pipeline ranged from a low of 10.1% to a high of 35.4%. As found in the simulations

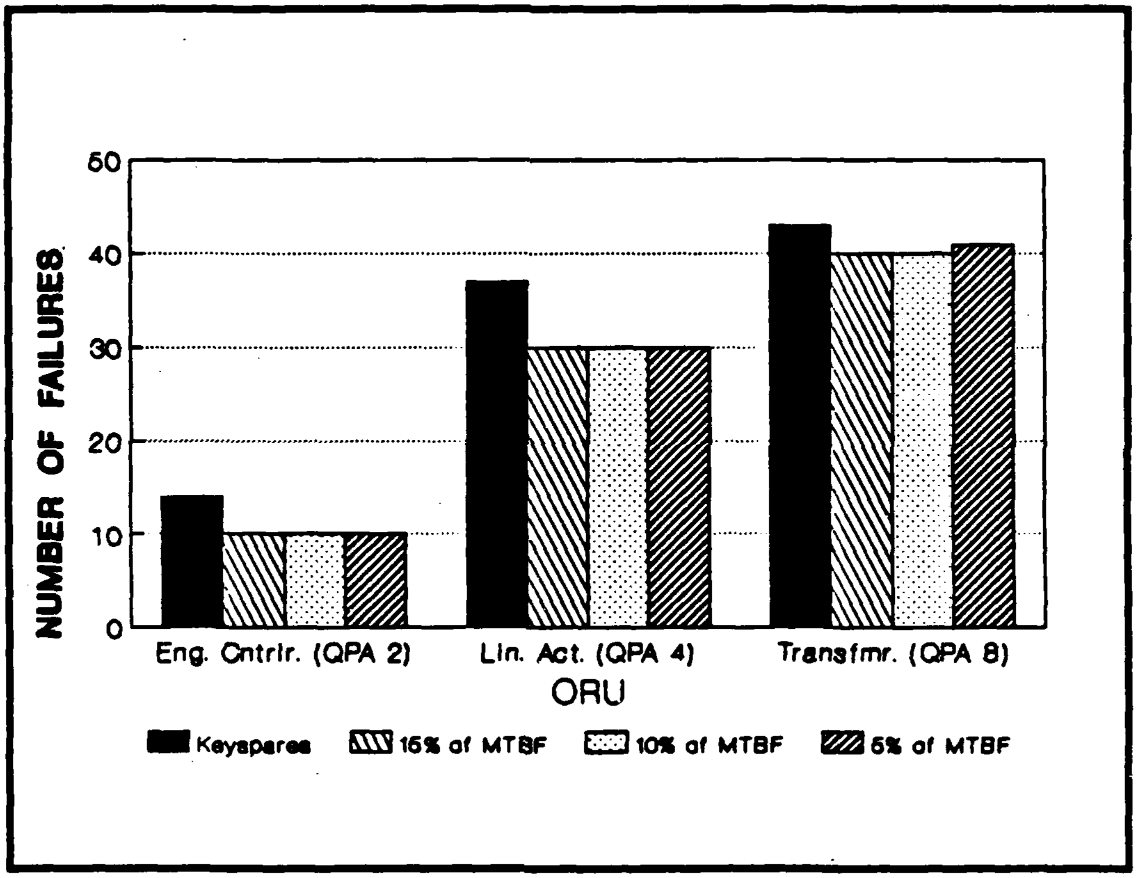


Figure 6. Number of ORU Failures (Normal Hazard Rate)

Table IV. Simulation Statistics (Normal Hazard Rate)

ORU	Std. Dev. Level	Avg. Downtime	% Time ORU Operational									% Time Spare Used	
Qty.		(Hrs.)	0	1	2	3	4	5	6	7	8	0	1
Eng. Cntrlr (OPA 2)	15%	80.0	0.010	5.040	94.900	-	-	-	-	-	-	10.300	89.700
	10%	35.0	0.010	4.830	95.100	-	-	-	-	-	-	10.400	89.600
	5%	245.0	0.050	4.940	95.000	-	-	-	-	-	-	10.100	89.900
Lin. Act. (OPA 4)	15%	0.0	0.000	0.000	0.790	13.400	85.700	-	-	-	-	29.000	71.000
	10%	0.0	0.000	0.390	13.600	13.600	85.800	-	-	-	-	29.100	70.900
	5%	0.0	0.000	0.000	0.640	14.000	85.200	-	-	-	-	29.100	70.900
Transfrmr. (OPA 8)	15%	0.0	0.000	0.000	0.000	0.000	0.000	0.110	1.650	16.800	81.400	34.900	65.100
	10%	0.0	0.000	0.000	0.000	0.000	0.000	0.100	1.430	16.800	81.500	35.400	64.600
	5%	0.0	0.000	0.000	0.000	0.000	0.010	0.060	1.580	16.700	81.600	35.300	64.700

under a constant ORU failure rate, these simulations again did not record any system downtime for the Linear Actuator U-Joint or Transformer ORUs.

Weibull Failure Rate Simulations

These simulations used the Weibull distribution with shape parameters less than one to generate ORU failures. Because the shape parameters were less than one, these simulations represent decreasing ORU failure rates. The detailed results of these simulations are presented in Appendix E.

Figure 7 compares the number of ORU failures computed by the Keyspares model versus the simulations under a Weibull ORU failure rate assumption. For these simulations, the shape parameter of the Weibull failure distribution was set at either 0.3, 0.5, 0.7.

The shape parameters were changed to evaluate the sensitivity of EPU ORU failures changes in the ORU failure rate. For example, with the shape parameter set at 0.3 the rate of initial ORU failure is greater than at 0.7.

As shown in Figure 7, the cumulative number of failures generated by the simulations were much smaller than the number of failures computed by the Keyspares model. As in the previous simulations, the total number failures generated increases as the number of on-board ORUs increases. No difference was observed in the number of ORU failures generated across the three levels of the shape

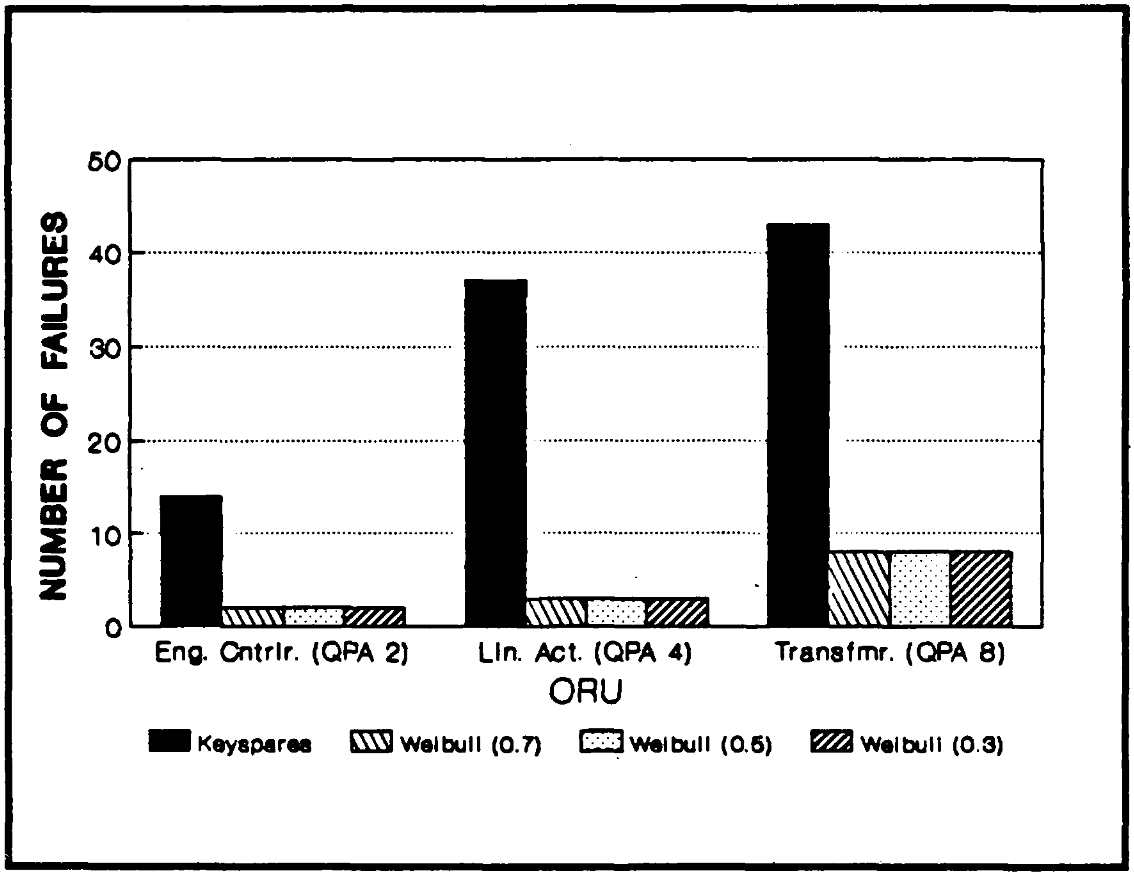


Figure 7. Number of ORU Failures (Weibull Hazard Rate)

parameter. One explanation for this observation is that the length of a simulation run was long, and not enough failures were generated early enough to observe a decreasing failure rate.

Table V presents the percent time a spare was available, percent time an ORU was operational at any given time, and system downtime statistics observed for the simulations under a Weibull ORU failure rate assumption. As shown in Table V, no system downtime was observed for any of the simulation runs. Also, the percentage of time the single spare was in the repair pipeline was very low for all simulations, ranging from 2.0% for the Engine Controller to 7.6% for the Transformer. Finally, there were only minor differences in either the percentage of time an ORU was operational or percentage of time the spare was in use across all three levels of the shape parameter.

Summary of Results

The statistics generated by these simulations confirm that an on-board ORU failure is a rare event. Consistently, the total number of failures generated were low considering the simulations encompassed a 50-year lifespan of the Space Station. There were only minor differences in the number of ORU failures computed by Keyspares and the ORU failures generated by the simulations under the exponential and normal ORU failure rate assumptions. Also, simulation generated failures were

Table V. Simulation Statistics (Weibull Hazard Rate)

ORU	Shape Parameter	Avg. Downtime	% Time ORU Operational									% Time Spare Used	
Qty.	(Hrs.)		0	1	2	3	4	5	6	7	8	0	1
Eng. Cntrlr (QPA 2)	0.3	0.0	0.0	1.0	99.0	-	-	-	-	-	-	2.0	98.0
	0.5	0.0	0.0	1.0	99.0	-	-	-	-	-	-	2.0	98.0
	0.7	0.0	0.0	1.0	99.0	-	-	-	-	-	-	2.0	98.0
Lin. Act. (QPA 4)	0.3	0.0	0.0	0.0	0.0	1.0	99.0	-	-	-	-	3.0	97.0
	0.5	0.0	0.0	0.0	0.0	1.0	99.0	-	-	-	-	3.0	97.0
	0.7	0.0	0.0	0.0	0.0	1.1	98.9	-	-	-	-	3.0	97.0
Transfrmr. (QPA 8)	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.0	96.0	7.0	93.0
	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.0	96.0	7.0	93.0
	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.0	96.0	7.5	92.5

consistently lower than ORU failures computed by Keyspares. When the resupply simulation was run under a Weibull failure rate, however, there was a very large difference in the total number of ORU failures.

The system downtime statistic provides some interesting findings. The Engine Controller ORU experienced downtime under both the exponential and normal ORU failure rate assumptions. System downtime was not observed for either the Linear Actuator U-Joint nor the Transformer ORUs. In other words, if using Keyspares' recommended spare levels Space Station operations would have been stopped for some period of time when failures were either exponentially or normally distributed.

Chapter Summary

This chapter presented the results of the simulations run to evaluate the effectiveness of the Keyspares sparing model. First, this chapter presented the results of the Keyspares algorithm for the EPU system for both a 30-year and 50-year time duration. Next, three sets of simulations were presented and their output statistics analyzed. The three sets of simulations used different ORU failure rate assumptions. First, the exponential ORU failure rate assumption was analyzed and compared to the results of the Keyspares model. Then two sets of simulations were analyzed varying the ORU failure rate assumptions.

Finally, a summary of the results of these simulations was presented. Chapter V presents the conclusions drawn from this research as well as recommendations for model improvements and future research.

V. Conclusions and Recommendations

Research Summary

The proposed Space Station represents a great technological achievement for the United States and plays a vital role maintaining the United States' superiority in space technology. Because the Space Station is a highly technical system, its support poses many new problems and challenges to space logisticians. Unique problems, such as transportation of supplies to the on-orbit platform, storage of critical supplies, maintenance of on-board systems and requirements determination will need to be solved in order to ensure adequate support of this complete system. Motivated by these problems and the critical need to support the Space Station, this research effort focused on the problem of supply support and specifically on spare support of critical Space Station components.

Currently, NASA employs the Keyspares sparing model to determine spare ORU requirements necessary to support the Space Station. This model is primarily used as an "up-front" logistical management tool to calculate lifetime spare ORU levels. These spare levels are used to determine long-range procurement needs of critical Space Station systems (27).

This research investigated the effectiveness of the Keyspares sparing model by analyzing its assumption of a constant ORU failure rate. Two research questions underlie this study.

1. Is Keyspares a good model for calculating on-board spare requirements, and is its assumption of a constant ORU failure rate valid?

2. What changes in spare requirements and lifetime EPU support occur if the constant ORU failure rate assumption is changed?

In order to answer these questions, a simulation of the EPU ORU failure and resupply system was created. This simulation modeled the resupply environment of an EPU ORU. Model input parameters such as resupply transit time, repair turn-around time, design MTBF and on-board ORU quantity were furnished by Space Station logistical personnel at KSC. These model parameters were used to simulate EPU ORU failures under three different failure rate assumptions. The first failure rate assumption was the exponential distribution's constant failure rate. The Keyspares sparing model assumes that ORU failures occur at a constant rate, characteristic of the exponential distribution. Next, the simulations were repeated under the assumptions of a normal (increasing) and Weibull (decreasing) ORU failure rates. Finally, results of these simulations were compared to the Keyspares model's output.

Research Conclusions

A definitive conclusion concerning the adequacy of the Keyspares is not possible since it estimates lifetime ORU failures and spare requirements for a Space Station that only exists on paper. This fact is also true of the simulation developed to model the Space Station's resupply system; the Space Station does not yet exist and any parameters used in these models are only "best-guesses" as to what the real Space Station resupply environment will be. In light of this problem, only inferences should be made to the adequacy of Keyspares.

The results of this research present three basic findings:

1. The occurrence of an on-board ORU failure is a "rare event." For both the Keyspares model and the simulations very few ORUs failed in the 50-year Space Station lifetime. This finding is directly attributable to the estimated high design MTBFs of the analyzed EPU ORUs. Differences in the average number of ORU failures between the Keyspares and simulation models were observed, but only the simulations with a Weibull ORU failure rate appeared to vary greatly from the Keyspares' ORU failure calculations.

2. The level of on-board ORU redundancy made a significant difference in the observed system downtime. A critical requirement of Keyspares is that only one ORU must be functioning for the entire EPU system to operate. Only

the Engine Controller ORU, with an on-board quantity of two, produced any system downtime. The Linear Actuator U-Joint and Transformer, with on-board quantities of four and eight respectively, produced no system downtime. It can be inferred that ORUs with low levels of system redundancy become the critical limiting factors to the survivability of the Space Station. Although system failure was a rare occurrence, it represents a catastrophic event, directly affecting the safety of the Space Station crew. It might be argued that the monetary trade-offs between the the cost of an extra spare versus the safety of the crew is a moot point. The simulations show, at least for the Engine Controller ORU, that Keyspares underestimated the number of spares required to support the critical EPU system.

3. Finally, the research demonstrates the Keyspares model is an adequate model in determining lifetime spare requirements for ORUs with a high design MTBF, a high degree of on-board system redundancy, and a constant failure rate. The research also demonstrates, however, that Keyspares underestimates spare support levels when the on-board redundancy is low combined with a normal failure rate.

Other criticisms of the Keyspares model are as follows:

1. Keyspares does not take into account the physical characteristics of the spare. For example, the size, weight and shape of an asset may be a limiting factor in storing and transporting the spare. In addition, the decision not to preposition spare ORUs aboard the Space Station might have drastic future consequences.

2. Keyspares does not address the cost of the spare. There is no methodology to conduct a benefit to cost analysis to the number of spares required. Spare levels for components that are relatively inexpensive may be increased to ensure a higher system availability.

3. Keyspares is very dependent on the accuracy of contractor-provided design MTBF values and that the spares are adequately "burned-in" to ensure adequate levels of operability.

Methodological Issues

Three significant methodological questions arose during the research.

1. The simulation developed was highly dependent on ORU data provided by KSC. Model input data such as design MTBF and on-board quantity play a significant role in the results generated by the simulations. This data was assumed to be correct.

2. The assumptions used in developing the simulation were provided by KSC. Assumptions such as the repair turn around time and the number of resupply missions

represented educated guesses as to what the real Space Station resupply environment will be.

3. Finally, the simulation developed assumed a worse case scenario. That is, every generated ORU failure had to assume the longest possible transit time to and from the Space Station to earth repair. Obviously, this will not always be the case during normal Space Station operations.

Suggestions For Future Research

This research effort suggests three possible areas for future research:

1. Develop a sparing algorithm that accounts for all asset characteristics. For example, a spares requirement model that considers the benefit to cost gain of additional spares would be a valuable tool in the management of Space Station spare requirements.

2. Once the final Space Station configuration is known, develop an in-depth simulation of the Space Station environment. The inclusion of factors, such as storage capacity requirements, maintenance actions requirements and the interchangeability of components will provide insight to future supply support problems.

3. Develop a method to evaluate the impact of poor supply support for space-based systems. Identify the cost of not having an ORU at the right place at the right time in terms of mission and crew safety.

Recommendations

The Space Station will represent America's highest achievement in space technology, and be a challenge for space logisticians of all fields. As demonstrated by this research, many questions remain on how logisticians are going to support a unique system like the Space Station. This research recommends that an integrated, "up-front" approach be applied to solving these critical support problems. Use of advanced problem solving techniques, such as expert systems, decision support systems and simulations should be stressed to not only solve difficult logistical questions, but to provide logistical support at the lowest possible cost.

Appendix A: Keyspares User Guide

Space Station

KEYSPARE USER'S GUIDE

BOEING AEROSPACE OPERATIONS COMPANY

Cocoa Beach, Florida 32931

KEYSPARE

Space Station Failures and Spares
Quantification Model

USER'S GUIDE

This User's Guide is being prepared for use with the BAO/KSC Spares Quantification Model. This model is available in stand-alone form (KEYSPARE) for the IBM PC/XT or compatibles as well as for use in conjunction with the SIMSYLS model (SIMSPARES), currently resident on the Apollo DN3000 workstation being developed and delivered under the ILS System Development Study Contract. This User's Guide will only present information on the use of the KEYSPARE Model.

1.0 INTRODUCTION

This User's Guide is intended to provide the user of the KEYSPARE model with sufficient information to make input to and receive output from the model. The model is extremely straightforward in its presentation style, asking questions and prompting the user for input as necessary. This guide will familiarize the user with the terminology utilized within the model, both for input and output parameters, as well as providing the user with a description of the questions encountered during use of the model.

1.1 PURPOSE

This User's Guide is being provided to fulfill requirements for documentation of the Spares Quantification Model developed under the auspices of the ILS System Development Study for SS/LSO at Kennedy Space Center.

1.2 SCOPE

This User's Guide is intended to provide direction for the Users of the KEYSPARE version of the Spares Quantification Model. The users of SIMSPARES will find information concerning the use of that specific version of the model in the SIMSYLS User's Guide.

1.3 BACKGROUND

The model was originally developed to predict failure quantification using a Poisson distribution on a hand-held programmable calculator. As the need for a more definitive model became evident, the decision was made to translate the model into a PC-based Fortran version. This version originally provided for two types of input to the model. Upon entry the user was asked to choose either keyboard or file I/O. Keyboard I/O gave the user immediate response on an item-by-item basis. File I/O prompted the user for input and output file names, then provided a tabular report of all results. This version is what eventually became SIMSPARES.

Since SIMSPARES provides for File I/O, the PC-based version became a stand-alone model, strictly providing for keyboard input and screen output. A new question was inserted to allow the user to enter a variable resupply cycle time. The original version assumed a 45 day resupply cycle. The user now must respond with a Resupply Cycle Time value which re-

mains effective for the entire KEYSPARE session.

1.4 HARDWARE REQUIREMENTS

The KEYSPARE Model was developed on a PC/XT compatible Zenith Z-158 computer. The model will run on any 8086 or 8088 based machine with an 8087 math coprocessor. The model does not require any supplemental RAM beyond the basic 256k generally available on any PC/XT compatible.

1.5 SOFTWARE REQUIREMENTS

The model is written and compiled in the Microsoft Fortran Compiler. This requires that the model be operated within the MS-DOS environment. General use of the model will not require a copy of the Fortran Compiler. The compiler will only be necessary to make changes to the program structure, algorithm or I/O presentation. ("Microsoft" and "MS-DOS" are registered trademarks of the Microsoft Corporation)

2.0 USE OF THE "KEYSPARE" MODEL

The model will run equally well whether installed on a "hard" disk drive, or invoked from a "floppy" drive. To install on a "hard" drive, enter the path where you wish the model to reside, then type "COPY A:KEYSPARE.EXE" followed by a Carriage Return (hereafter designated by "<Cr>"). This will copy the executable Fortran file to the "hard" drive, which is the only file required for running the model. Thereafter, to execute the model, simply enter the path where the model resides and type "KEYSPARE" followed by a <Cr>.

The model can be executed from the "floppy" drive simply by typing "A:KEYSPARE" followed by a <Cr>.

Once the model has been invoked, several information screens are encountered which give general information concerning the model and its functions. After the Title screen (see fig. 1), an information screen appears (fig. 2) which tells the User that certain inputs will evoke responses out of the computational range of the machine. This is due to the structure of the equation used for the estimation of failures to be expected during the Space Station Program lifetime. This information screen gives general guidelines for data ranges. Data is not required to be within the specified ranges, as measurement of key parameters is made during computation. If the data entered will produce results out of the machine's computational range, the model continues processing data until the limit is exceeded, then returns an error message with

the status of the computed parameters at that point. This will be explained in more detail in section 2.2, MODEL OUTPUT.

```
********** SPARES **********

A RELIABILITY BASED FAILURE/SPARES QUANTIFICATION MODEL

VERSION 2.00

(C) 1987
JIM WERPY
BOEING AEROSPACE OPERATIONS


Pause.
Please press <return> to continue.
```

fig. 1

```
     THIS PROGRAM WILL EVALUATE THE NUMBER OF SPARES
REQUIRED TO SUPPORT AN ORU OF A SPECIFIC TYPE DURING A
SPECIFIED NUMBER OF YEARS OF SPACE STATION OPERATION.
YOU WILL BE ASKED 6 QUESTIONS.  BE AWARE THAT BOUNDS
EXIST FOR THE RESPONSES YOU PROVIDE.  HIGH ORU COUNT
COUPLED WITH EXTREMELY LOW MTBF AND THE FULL COMPLEMENT
OF OPERATING HOURS WILL EXCEED THE CAPACITY OF THE
MACHINE.  AS A GENERAL RULE, USE A TOTAL OF 100 ORU"S
OR LESS AND USE MTBF"S OF 25,000 HOURS OR MORE.

 ***** FOLLOW ALL RESPONSES WITH A CARRIAGE RETURN. *****
Pause.
Please press <return> to continue
```

fig. 2

2.1 MODEL INPUT

The following is a list of the model input parameters:

> **Resupply Cycle Time** - the designated number of days between scheduled orbiter resupply missions. This parameter is only entered once for a single program run.
>
> **Number of ORU's Installed On-orbit** - the quantity of a specific type of ORU installed on-orbit.
>
> **ORU MTBF** - the design Mean Time Between Failure for the ORU under analysis.
>
> **Average Annual Operating Hours** - the average number of hours per year the ORU under analysis is in operation.
>
> **Dictated Probability** - the probability of mission success. Generally related to the availability factor generated by the criticality of the ORU under analysis. For example, Criticality 1 items are usually assigned a dictated probability value of .99, Criticality 2 a value of .95, etc.
>
> **ORU Turnaround Time** - the time required to repair and refurbish an ORU after return to the ground

Input of model parameters is made by simply answering questions as they appear on the screen. The first question encountered prompts the user to enter the length of Resupply Cycle Time. See fig. 3. The prompt indicates common values of 45, 90 or 120 days for this figure, as well as indicating that 90 days is the default value.

```
LENGTH OF RESUPPLY CYCLE WILL AFFECT THE OUTCOME
OF THE SPARES MODEL.  THIS FIGURE IS GENERALLY LIMITED TO
45, 90 OR 120 DAY LENGTHS.  DEFAULT VALUE = 90 DAYS.
ENTER THE VALUE YOU WISH TO UTILIZE FOR THIS SERIES
OF SPARES PROGRAM RUNS.
```

---

fig. 3

The value for Resupply Cycle Time may now be entered, and must be followed by a <Cr>. Striking only a <Cr> at this

point will assign a value of 90 to Resupply Cycle Time for the current session of "KEYSPARE". In order to change this for different ORU's, the program must be exited and reinvoked to reassign a new value to this parameter.

On every pass through the model, the current value of Resupply Cycle Time will be echoed to remind the user of the current value for this parameter.

The Resupply Cycle Time value is displayed, and the user is now prompted for values for the 6 remaining parameters. Responding to each question, the user enters data in the format shown in fig. 4.

```
RESUPPLY CYCLE =     90 DAYS
ENTER THE NUMBER OF ORUs INSTALLED ON-ORBIT-
24
ENTER THE ORU MTBF IN HOURS-
55000
ENTER AVERAGE ANNUAL OPERATING HOURS-
1 YEAR = 8760 HRS. (DEFAULT)

8760.00
ENTER THE NUMBER OF YEARS OF OPERATION-
30
ENTER THE DICTATED PROBABILITY VALUE-
FOR EXAMPLE, CRIT 1 ITEMS USE .99
             CRIT 2 ITEMS USE .95
             CRIT 3 ITEMS USE .90
HOWEVER, YOU MAY USE ANY VALUE YOU WISH.
90
ENTER THE ORU TURNAROUND TIME IN WHOLE DAYS-
350
```

fig. 4

Fig. 4 shows the input values for a fictional model run. The values utilized will yield results as seen in section 2.2, Model Output. This series of questions in this format is repeated for each ORU input.

The third question on this screen refers to Average Annual Operating Hours, and indicates a default value of 8760 hours. Striking a <Cr> at this point will assign a value of 8760.00 to Average Annual Operating hours. Any value between 0 and 8760 will work. Any value greater than 8760 will display an error message and prompt the user for new values.

2.2 MODEL OUTPUT

There are two model output formats. The normal format, (fig. 5) is the format encountered when normal calculations do not exceed certain model limits. These limits are set in order to exit the model prior to a machine math error, which is fatal to the run of the model. When those limits are exceeded, the alternate format (fig. 6) is displayed.

Both outputs echo all pertinent input data except for ORU Turnaround time. Since this value is not important in establishing Poisson failures, but only important in determining spares quantities required to support the failures, the value was not echoed to the output screen.

Fig. 5 shows the normal data output format. Data is echoed within a narrative. "129 changeouts" refers to the number of failures which were generated by the Poisson summation. Finally, the model indicates the number of spares required to support this number of failures based on the ORU Turnaround Time previously input.

```
FOR         24 ORUs OF 1 TYPE INSTALLED ON-ORBIT,
WITH AN MTBF OF          55000 HOURS, AND 8760.00
AVERAGE ANNUAL OPERATING HOURS, THE ORU WILL
UNDERGO       129 CHANGEOUTS IN A      30
YEAR PERIOD OF SPACE STATION OPERATION.
DICTATED PROBABILITY = .90
RESUPPLY CYCLE =   90 DAYS

********************************
*** SPARES REQUIRED =     2    ***
********************************
      DO YOU WISH TO CONTINUE? (Y OR N + RTN)
```

fig. 5

Fig. 6 shows the alternate data format encountered after reaching the limitations of the model. A narrative paragraph indicates the error condition, which is then followed by a tabular listing of output data. "CHANGEOUT COUNT" refers, again, to the number of failures generated by the Poisson summation. This is the current value of the number of failures, prior to encountering the error. This value is flagged with a "*NO CONFIDENCE*" message to indicate the insubstantial nature of this value. "SPARES COUNT" refers to the number of spares required to support the indicated number of failures, or Changeout Count. Again, this value is flagged with a "*NO CONFIDENCE*" message. The "ASSESSED PROBABILITY" value is the total currently assigned to the Poisson

summation, which is being checked against the "DICTATED PROBABILITY" value to provide a loop control within the model. Assessed and Dictated Probability values are displayed as a measure of how 'close' the model is to achieving a useful set of output data. More information will follow in section 2.3, entitled "The Reliability Equation and Model Limitations".

The major differences between the two outputs lie in the presentation of the output data and in one data element. Fig. 6 shows the alternate output format.

```
     FIGURES USED FOR THIS ORU WILL PRODUCE A
 MACHINE ERROR - REAL MATH OVERFLOW.  PLEASE MODIFY
 YOUR VALUES AND TRY AGAIN OR EXIT BY NEXT STATEMENT.

        CHANGEOUT COUNT=                   145  *NO CONFIDENCE*
        SPARES COUNT=                        2  *NO CONFIDENCE*
        ASSESSED PROBABILITY=    .889388D+00
        DICTATED PROBABILITY=    .980000D+00
        NUMBER INSTALLED=                   25
        MTBF=                            50000
        AVG. ANN. OP. HRS.=            8760.00
        # YRS OF OPERATION=                 30
        # DAYS IN RESUPPLY CYCLE=           90
Pause.
Please press <return> to continue.
        DO YOU WISH TO CONTINUE? (Y OR N + RTN)
```

fig. 6

2.3 THE RELIABILITY EQUATION AND MODEL LIMITATIONS

Model limitations must be understood in order to interpret the data for meaningful results. The purpose of the information screen (fig. 2) is to forewarn the model user that ranges and relationships between data items can affect model output.

The failures generated by the Poisson summation within the model are a function of the number of iterations of the summation. In other words, the number of failures generated is equal to the current index of the summation. The summation of the following general reliability equation is the basis of the failures quantification:

$$\frac{\beta^{x}\, e^{(-\beta)}}{x!}$$

where: $\beta = \dfrac{kt}{mtbf}$

	k = Quantity installed	(Number of ORU's)
	t = total operating time	(Avg. Ann. Op. Hrs. x # yrs. of operation)
	mtbf = Mean Time Between Failure	(ORU MTBF)
	x = summation index	

This equation is summed iteratively until the sum is greater than or equal to the Dictated Probability. This sum is called the Assessed Probability.

As you may notice, the value of beta (β) remains fixed for any specific ORU. This value is raised to the index of the summation. As the value of the summation index approaches 145, the first term of the numerator reaches a significantly high value. This is the value which, if not checked, will produce a machine error known as a Real Math Overflow. The exponential term in the numerator remains constant with each summation iteration and has no effect on the machine error. By checking the value of the first term of the numerator prior to incrementing the summation index, the model can exit if an out-of-range limit value is encountered or exceeded.

Generally, if an ORU has a low MTBF (e.g., under 50000 hrs.), and a large population (e.g., more than 25 like items), the model will respond with the alternate output screen (fig. 6). The first two numbers encountered are 1) the quantified failures and 2) the spares required to support that number of

failures. These items are flagged as "*NO CONFIDENCE*" values and should only be used for comparisons of other unsuccessful ORU runs. This output screen also gives the current values for the Assessed and Dictated Probabilities. The Assessed value can be compared to the Dictated value to verify how 'close' the Probability values are, as these are the values which are compared to control the summation iteration.

Other limitations of the model must also be considered. The quantification method utilized in the model does not account for spares to replace the following types of failures:

1) Infant failures. A high incidence of infant failures may result from undetected failure modes.

2) Test failures. Unforeseen stress factors invoked during the test phase of a program may cause additional unplanned failures for an ORU.

3) A&CO failures. Untested assembly sequences or unexpected anomalies encountered during Assembly and Checkout may induce additional unplanned failures.

Spares to support repair of these types of failures should be enumerated by an analysis method or by policy directive. In general, most programs of similar scope to Space Station purchase a quantity of spares recommended via analysis (i.e., via a model such as KEYSPARE), as well as a set quantity or percentage of spares to support these additional types of failures.

The model does not deal with dependent, or cascading, failures. These failures are the type which occur as the result of the specific failure of a related or connected ORU at some other point in the system, and are generally not predictable. Failures of this type are highly affected by configuration and redundancy considerations. For instance, serial redundancy may have a more significant impact on dependent failure occurrence than parallel redundancy.

APPENDIX A

DATA ELEMENT DICTIONARY

APPENDIX A

DATA ELEMENT DICTIONARY

1) Field Name - variable designation of the input quantity.

2) Field Length - expressed as a number of characters for a numeric field. For numeric fields, it is expressed in the form of X.Y where X = the total number of characters (including the decimal point) and Y = the number of fixed decimal places.

3) Type - designated as either alphanumeric (A), integer (I) or real (F).

4) Description - explains, in detail, the content required by each data element.

001	CTIME	4.0	I

Resupply Cycle Time. Defined as the nominal time between orbiter resupply flights. Entered as the nominal time in whole days between orbiter resupply launches.

002	N	8.0	I

ORU Quantity. Defined as the number of like ORU's performing like funct ons on-orbit. This means that all ORU's of the same configuration installed to perform like functions should be analyzed as a single ORU.

003	MTBF	12.0	I

ORU Mean Time Between Failure. Defined as the average time to failure for a specific ORU in a specific installed configuration.

004	T	7.0	F

Average Annual Operating Hours. Defined as the mean number of hours per year the ORU can be expected to be active in its specific configuration.

005	Y	6.0	I

Number of Years of Operation. Defined as the expected program lifetime in years.

006	P	3.2	F

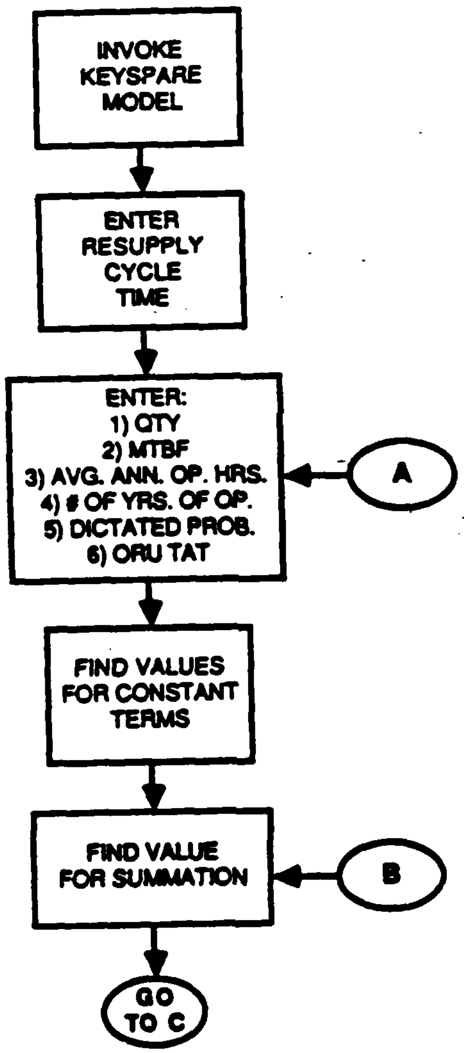
Dictated Probability. Defined as the probability value to be met or exceeded by the reliability summation. The Dictated Probability is essentially the probability of mission success.

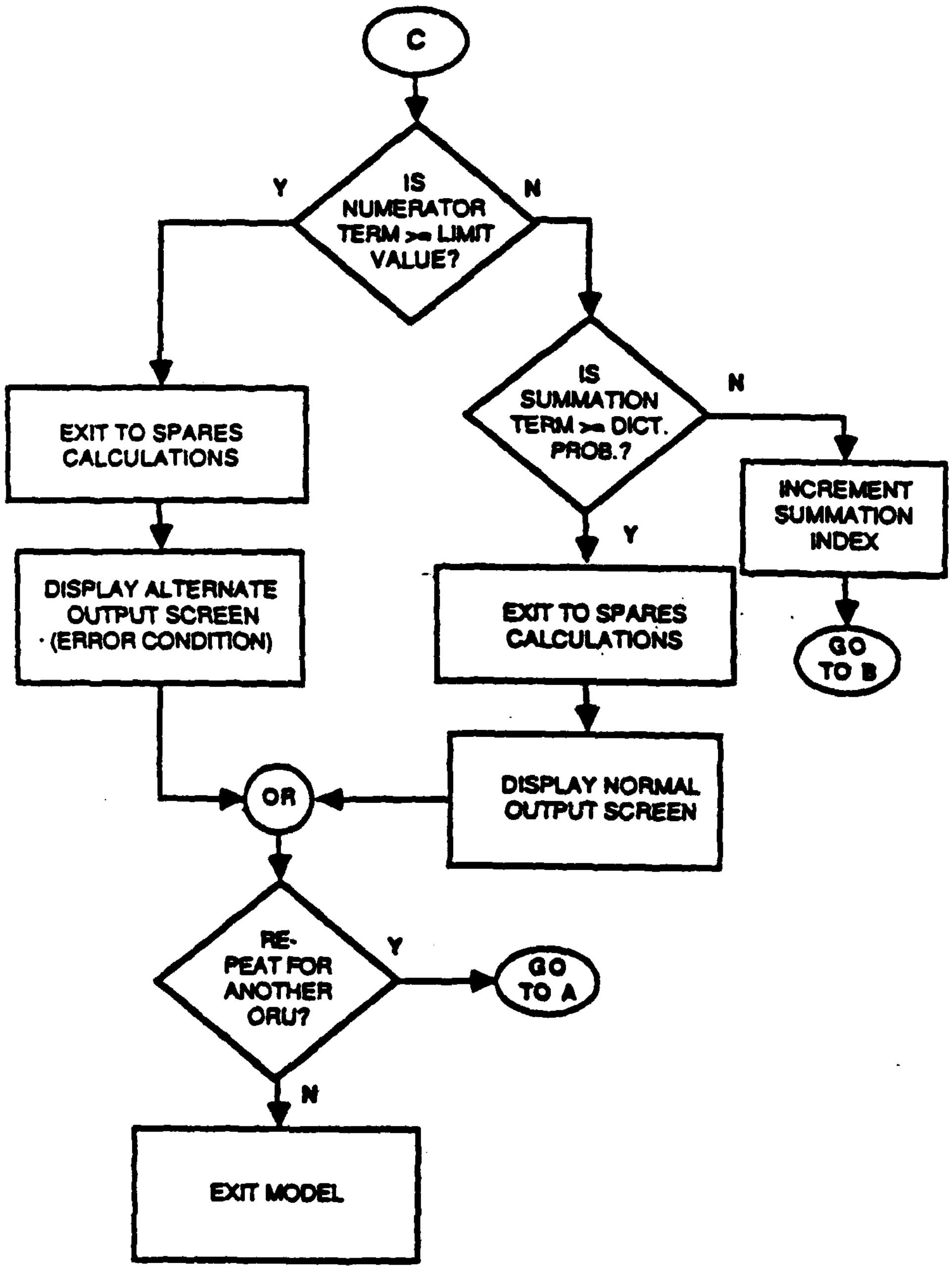
007	TAT1	6.0	I

ORU Turnaround Time. Defined as the average time in days from ORU return to earth until the ORU is again ready for launch on an orbiter resupply flight.

APPENDIX B

PROGRAM FLOW


INVOKE KEYSPARE MODEL
ENTER RESUPPLY CYCLE TIME
ENTER:
1) QTY
2) MTBF
3) AVG. ANN. OP. HRS.
4) # OF YRS. OF OP.
5) DICTATED PROB.
6) ORU TAT
A
FIND VALUES FOR CONSTANT TERMS
FIND VALUE FOR SUMMATION
B
GO TO C


C
IS NUMERATOR TERM >= LIMIT VALUE?
Y
N
EXIT TO SPARES CALCULATIONS
DISPLAY ALTERNATE OUTPUT SCREEN (ERROR CONDITION)
IS SUMMATION TERM >= DICT. PROB.?
N
Y
INCREMENT SUMMATION INDEX
GO TO B
EXIT TO SPARES CALCULATIONS
DISPLAY NORMAL OUTPUT SCREEN
OR
RE-PEAT FOR ANOTHER ORU?
Y
GO TO A
N
EXIT MODEL

Appendix B: Keyspares FORTRAN Computer Code

```
      PROGRAM SPARES
C       A RELIABILITY BASED FAILURE/SPARES QUANTIFICATION MODEL
C                              BY JIM WERPY
C                              VERSION 2.00
C                                (C) 1987
C                                JIM WERPY
C                      BOEING AEROSPACE OPERATIONS
C     THIS PROGRAM WILL EVALUATE THE NUMBER OF SPARE ORU'S
C     NECESSARY TO SUPPORT A SPECIFIED NUMBER OF YEARS OF SPACE
C     STATION OPERATION.  THIS VERSION FOR KEYBOARD/SCREEN I/O ONLY.
      INTEGER X,M,N,MTBF,Y,TAT1,QUAN,CTIME
      REAL*8 T,P,T2,A,B,C,NUM,QUO,SUM,P2,XFACT,D,TEMP,E
      CHARACTER*1 RESPONSE
      WRITE (*,5000)
 5000 FORMAT (21X,'********** SPARES **********',/,/,10X,'A RELIABILITY
     +BASED FAILURE/SPARES QUANTIFICATION MODEL',/,/,29X,'VERSION 2.00'
     +/,/,31X,'(C) 1987',/,31X,'JIM WERPY',/,21X,'BOEING AEROSPACE OPER
     +TIONS')
      PAUSE
    4 WRITE (*,1)
    1 FORMAT (/,/,/,/,/,/,
     +7X,'THIS PROGRAM WILL EVALUATE THE NUMBER OF SPARES ',/,
     +2X,'REQUIRED TO SUPPORT AN ORU OF A SPECIFIC TYPE DURING A',/,
     +2X,'SPECIFIED NUMBER OF YEARS OF SPACE STATION OPERATION.',/,
     +2X,'YOU WILL BE ASKED 6 QUESTIONS.  BE AWARE THAT BOUNDS',/,
     +2X,'EXIST FOR THE RESPONSES YOU PROVIDE.  HIGH ORU COUNT',/,
     +2X,'COUPLED WITH EXTREMELY LOW MTBF AND THE FULL COMPLEMENT',/,
     +2X,'OF OPERATING HOURS WILL EXCEED THE CAPACITY OF THE',/,
     +2X,'MACHINE.  AS A GENERAL RULE, USE A TOTAL OF 100 ORU"S',/,
     +2X,'OR LESS AND USE MTBF"S OF 25,000 HOURS OR MORE.',/,/,
     +2X,'***** FOLLOW ALL RESPONSES WITH A CARRIAGE RETURN. *****')
      PAUSE
    2 WRITE (*,4100)
 4100 FORMAT (/,/,/,/,/,/,/,/,
     +7X,'LENGTH OF RESUPPLY CYCLE WILL AFFECT THE OUTCOME',/,
     +2X,'OF THE SPARES MODEL.  THIS FIGURE IS GENERALLY LIMITED TO',/,
     +2X,'45, 90 OR 120 DAY LENGTHS.  DEFAULT VALUE = 90 DAYS.',/,
     +2X,'ENTER THE VALUE YOU WISH TO UTILIZE FOR THIS SERIES',/,
     +2X,'OF SPARES PROGRAM RUNS.',/,/,/,/,/)
      READ (*,4105,ERR=585) CTIME
 4105 FORMAT (I4)
      IF (CTIME .EQ. 0) CTIME = 90
    5 WRITE (*,9) CTIME
    9 FORMAT (1X,'RESUPPLY CYCLE = ',I4,' DAYS')
      WRITE (*,10)
   10 FORMAT (1X,'ENTER THE NUMBER OF ORUs INSTALLED ON-ORBIT- ')
      READ (*,15,ERR=575) N
   15 FORMAT (I8)
   17 WRITE (*,20)
   20 FORMAT (1X,'ENTER THE ORU MTBF IN HOURS- ')
      READ (*,25,ERR=575) MTBF
   25 FORMAT (I12)
      WRITE (*,30)
   30 FORMAT (1X,'ENTER AVERAGE ANNUAL OPERATING HOURS- ',/,
     +1X,'1 YEAR = 8760 HRS. (DEFAULT)')
      READ (*,35,ERR=575) T
```

```
35    FORMAT (F7.0)
      IF (T .EQ. 0.) T = 8760.
      WRITE (*,38) T
38    FORMAT (1X,F7.2)
      IF (T .GT. 8760.) GOTO 260
      WRITE (*,40)
40    FORMAT (1X,'ENTER THE NUMBER OF YEARS OF OPERATION- ')
      READ (*,45,ERR=575) Y
45    FORMAT (I6)
      WRITE (*,500)
500   FORMAT (1X,'ENTER THE DICTATED PROBABILITY VALUE- ',/,
     +5X,'FOR EXAMPLE, CRIT 1 ITEMS USE .99',/,
     +5X,'             CRIT 2 ITEMS USE .95',/,
     +5X,'             CRIT 3 ITEMS USE .90',/,
     +5X,'HOWEVER, YOU MAY USE ANY VALUE YOU WISH.')
      READ (*,550,ERR=575) P
550   FORMAT (F3.2)
      WRITE (*,560)
560   FORMAT (1X,'ENTER THE ORU TURNAROUND TIME IN WHOLE DAYS- ')
      READ (*,565,ERR=575) TAT1
565   FORMAT (I6)
      GOTO 48
575   WRITE (*,580)
580   FORMAT (3X,'*** INPUT ERROR ***',/,/,3X,'REENTER VALUES AND
     +TRY AGAIN.')
      GOTO 5
585   WRITE (*,580)
      GOTO 2
C     THE FOLLOWING ROUTINE IS THE EVALUATION OF THE ORU'S FAILURES
C     BASED ON THE POISSON DISTRIBUTION.
48          X=0
            QUAN=0
            SUM=0.0
            T2= Y * T
            A = N * T2 / MTBF
            D=-1.*A
            B=DEXP (D)
50          C=A**X
            NUM = B * C
            TEMP=1
            IF (X.EQ.0) GOTO 80
            CALL FACT (X,TEMP)
80          XFACT = TEMP
            QUO = NUM / XFACT
            IF (QUO .EQ. 0.0) QUO = 4.2D-307
            SUM = SUM + QUO
            IF (C .GT. 5.0D+305) GOTO 300
            IF (SUM .GE. P) GOTO 200
            X = X+1
            GOTO 50
200         P2 = 100 * P
            CALL SPCALC (X,Y,TAT1,QUAN,CTIME)
      WRITE (*,205) N,MTBF,T,X,Y,P,CTIME,QUAN
205   FORMAT (5X,'FOR ',I8,' ORUs OF 1 TYPE INSTALLED ON-ORBIT,',/,
     +5X,'WITH AN MTBF OF ',I12,' HOURS, AND ',F7.2,/,
     +5X,'AVERAGE ANNUAL OPERATING HOURS, THE ORU WILL',/,
```

```
     +5X,'UNDERGO  ',I6,' CHANGEOUTS IN A ',I6,/,
     +5X,'YEAR PERIOD OF SPACE STATION OPERATION.',/,
     +5X,'DICTATED PROBABILITY = ',F3.2,/,
     +5X,'RESUPPLY CYCLE = ',I4,' DAYS',/,/,
     +5X,'*********************************',/,
     +5X,'*** SPARES REQUIRED = ',I4,'    ***',/,
     +5X,'*********************************')
 238  WRITE (*,240)
 240  FORMAT (10X,'DO YOU WISH TO CONTINUE? (Y OR N + RTN)')
      READ (*,250) RESPONSE
 250  FORMAT (A1)
      IF (RESPONSE .EQ. 'Y') THEN
            GOTO 5
      ELSEIF (RESPONSE .EQ. 'y') THEN
            GOTO 5
      ELSEIF (RESPONSE .EQ. 'N') THEN
            GOTO 280
      ELSEIF (RESPONSE .EQ. 'n') THEN
            GOTO 280
      ELSE
            GOTO 238
      ENDIF
 260  WRITE (*,270)
 270  FORMAT (1X,'YOU HAVE EXCEEDED THE TOTAL NUMBER OF HOURS IN',/,
     +1X,'ONE YEAR.  LET"S START OVER!')
      PAUSE
      GOTO 5
 300  CALL SPCALC (X,Y,TAT1,QUAN,CTIME)
      WRITE (*,310) X,QUAN,SUM,P,N,MTBF,T,Y,CTIME
 310  FORMAT (8X,'FIGURES USED FOR THIS ORU WILL PRODUCE A',/,
     +3X,'MACHINE ERROR - REAL MATH OVERFLOW.  PLEASE MODIFY',/,
     +3X,'YOUR VALUES AND TRY AGAIN OR EXIT BY NEXT STATEMENT.',/,/,
     +10X,'CHANGEOUT COUNT= ',23X,I6,2X,'*NO CONFIDENCE*',/,
     +10X,'SPARES COUNT= ',28X,I4,2X,'*NO CONFIDENCE*',/,
     +10X,'ASSESSED PROBABILITY= ',12X,D12.6,/,
     +10X,'DICTATED PROBABILITY= ',12X,D12.6,/,
     +10X,'NUMBER INSTALLED= ',20X,I8,/,
     +10X,'MTBF= ',28X,I12,/,
     +10X,'AVG. ANN. OP. HRS.= ',19X,F7.2,/,
     +10X,'# YRS OF OPERATION= ',20X,I6,/,
     +10X,'# DAYS IN RESUPPLY CYCLE= ',16X,I4)
      PAUSE
      GOTO 238
 280  END
```

Name	Type	Offset	P	Class
A	REAL*8	2120		
B	REAL*8	2136		
C	REAL*8	2144		
CTIME	INTEGER*4	1298		
D	REAL*8	2128		
DEXP				INTRINSIC
E	REAL*8	*****		
M	INTEGER*4	*****		
MTBF	INTEGER*4	1446		

```
N       INTEGER*4       1398
NUM     REAL*8          2152
P       REAL*8          1944
P2      REAL*8          2184
QUAN    INTEGER*4       2100
QUO     REAL*8          2176
RESPON  CHAR*1          2868
SUM     REAL*8          2104
T       REAL*8          1554
T2      REAL*8          2112
TAT1    INTEGER*4       2014
TEMP    REAL*8          2160
X       INTEGER*4       2096
XFACT   REAL*8          2168
Y       INTEGER*4       1630
```

```
                    SUBROUTINE FACT (I,X)
                    REAL*8 X
                    X = 1
                    DO 100 J=1,I
1                       X = X * J
1           100     CONTINUE
                    RETURN
                    END
```

```
Name      Type            Offset P Class

I         INTEGER*4            0 *
J         INTEGER*4         3732
X         REAL*8               4 *
```

```
                    SUBROUTINE SPCALC (X,Y,TAT1,QUAN,CTIME)
                    REAL*8 A,B,C,D,E,K
                    INTEGER*4 I,J
                    INTEGER X,Y,TAT1,QUAN,CTIME
                    K = 8 * Y
                    A = X/K
                    B = TAT1/CTIME
                    I = B
                    C = B - I
                    IF (C .GT. 0.0) I = I + 1
                    D = I * A
                    J = D
                    E = D - J
                    IF (E .GT. 0.0) J = J + 1
                    QUAN = J
                    RETURN
                    END
```

```
Name      Type            Offset P Class

A         REAL*8            3748
B         REAL*8            3756
C         REAL*8            3768
```

```
CTIME   INTEGER*4          16 *
D        REAL*8          3776
E        REAL*8          3788
I        INTEGER*4       3764
J        INTEGER*4       3784
K        REAL*8          3740
QUAN     INTEGER*4         12 *
TAT1     INTEGER*4          8 *
X        INTEGER*4          0 *
Y        INTEGER*4          4 *


Name     Type          Size   Class

FACT                          SUBROUTINE
SPARES                        PROGRAM
SPCALC                        SUBROUTINE


 Pass One     No Errors Detected
             181 Source Lines
```

Appendix C: Fundamentals of SLAM II Networks

Introduction

This section acquaints the reader with some of the fundamentals of the SLAM II simulation language. Here, basic concepts of the SLAM II network are described in addition to the symbology used in a typical SLAM II network. For further details on network models, please refer to A. Alan B. Pritsker's book, Introduction to Simulation and SLAM II (18).

SLAM II is an advanced simulation language used to model and analyze real-life systems. SLAM II provides both a computer code and a system of graphical network symbols to model systems. This appendix will describe both the computer code and network symbology of six common SLAM II activities. This description is not inclusive of all SLAM II activities but represents only the most common activities used in the simulation developed in this study.

Create and Terminate Nodes

Create Node. The create node generates entities to be used in the system under study. An entity can represent anything the user requires for the study. In the simulation of this study, an entity represents a failure of an on-board, installed EPU ORU. The SLAM II computer code

and network symbol of the create node is presented as follows:

Code: CREATE, TBC, TF, MA, MC, M:

where:

TBC = Time of first entity creation

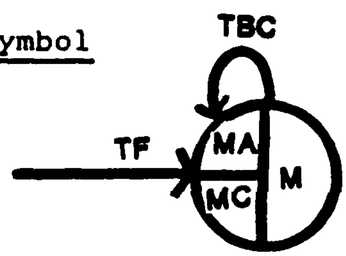
TF = Time between creations of entities (MTBF)

MA = The "birthday" or time when the entity was created

MC = The maximum number of entities to create

M = The number of branches the entity is to take when the entity exists the create node

Symbol



Terminate Node. The terminate node is used to destroy or delete entities from the SLAM II network (18:119).

Code: TERMINATE or TERM;

Symbol

Goon Nodes and Activities

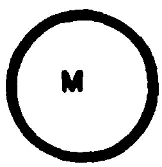
Goon Node. The go on or goon node is used as a continuation node to route entities over an activity or to another node (18:135).

Code: GOON, M;

where

M = The number of branches the entity must take when it exits the goon node. For example, if M = 1, and two decision branches follow the goon node, the entity must choose only one branch.

Symbol



Activities. Branches are used to model activities. Activities may represent a time duration, such as the transit time to the Space Station, probabilities or conditions. This study used branches to represent both time duration and conditions. For example, at goon node G2 two conditional branches were used as decision points. If the ground stock was greater than one the entity would go to goon node G3 but, if ground stock was less than or equal to zero the entity would go to goon node G5.

Code: ACTIVITY, DUR, PROB or COND, NLBL;

where:

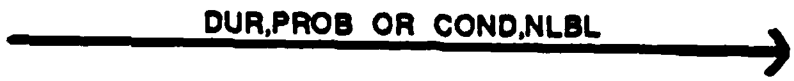
DUR = The time duration specified for that activity

PROB = The probability specification for selecting the activity

COND = The logical condition for selecting the activity

NLBL = The end node label where the user specifies the entity to go next if this branch is taken

Symbol



Assign Node. The assign node is used to prescribe values to system variables or attributes of an entity passing through the assign node. For example, at assign node A when an entity passes through this node the installed quantity, represented by system variable XX(1), was reduced by one.

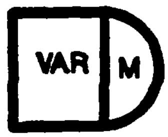
Code: ASSIGN, VAR, M;

where:

VAR = The specified system variable or entity attribute

M = The number of branches the entity is to take

Symbol



Statistical Collect Nodes. The collect node is used to collect statistics of model interest. In SLAM II, statistics can be collected on five types of variables at collect nodes.

3. Interval statistics. This statistic relates to the arrival time of an entity minus some specified attribute value of an entity (INT(I)) (18:136).

4. Time between entity arrivals (BET).

5. SLAM II system variable. This is the value of a SLAM II system variable which is recorded as an observation every time an entity arrives at a collect node (XX(N)).

For each of the five types of variables estimates for the mean and standard deviation of the variable are obtained. In addition to statistics, the collect node can also provide a histogram of the values collected at each collect node.

A special type of statistic in which SLAM II can monitor is the time persistent statistic. This statistic

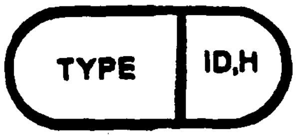
measures the total time a variable spends in a specified state. For example, this study monitored the total time when a spare was available.

<u>Code</u>: COLCT, TYPE, ID, HISTOGRAM;

where:

TYPE	=	One of the five types of statistics the user specifies to collect
ID	=	A label or name given to the collect node
HISTOGRAM	=	Parameters specified to create a histogram

<u>Symbol</u>



<u>Time Persistent Code</u>: TIMST, VAR, ID;

The time persistent command does not have a network symbol.

Appendix D: SLAM II Simulation Codes

This appendix presents the simulation codes used in developing the Space Station simulations. Only one simulation code is presented for the normal and Weibull distributions since the only differences are the levels of standard deviations or shape parameter.

ORU Name: Engine Cntrlr. QPA: 2 MTBF: 87600
Distribution: Exponential Shape Parameter: N/A
Standard Deviation: N/A

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
       XX(1),INST_QTY/
       XX(2),FAIL/
       XX(3),GS;
INTLC,INST_QTY=2;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=2;
TIMST,XX(1),INST_QTY HGM,3/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1    CREATE,EXPON(87600,1)1;
       ACT,0,INST_QTY.LT.1,STOP;
       ACT,0,,G1;
CP2    CREATE,EXPON(87600,2)1;
       ACT,0,INST_QTY.LT.2,STOP;
       ACT,0,,G1;
G1     GOON,1;
       ASSIGN,INST_QTY=INST_QTY-1;
       ASSIGN,XX(6)=XX(6)-1;
       ASSIGN,FAIL=FAIL+1,1;
       ACT,0,INST_QTY.EQ.0,A1;
       ACT,0,INST_QTY.GE.1,ORU;
A1     ASSIGN,XX(4)=TNOW;
       ACT,0,,ORU;
ORU    COLCT,INT(1),ORU_FAIL;
G2     GOON,1;
       ACT,0,GS.GE.1,G3;
       ACT,2160,GS.LE.0,RPR;
G3     GOON,2;
       ACT,0,,A2;
       ACT,4680,,G5;
A2     ASSIGN,GS=GS-1;
       ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G4     GOON,1;
       ACT,0,INST_QTY.EQ.0,A6;
       ACT,0,INST_QTY.GE.1,A7;
A6     ASSIGN,XX(5)=TNOW-XX(4);
       ASSIGN,XX(1)=XX(1)+1;
       ACT,0,,DT;
A7     ASSIGN XX(1)=XX(1)+1;
       TERM;
G5     GOON,1;
       ACT,0,XX(6).LT.2,G8;
       ACT,0,XX(6).EQ.2,A4;
A4     ASSIGN,GS=GS+1;
       TERM;
G6     GOON,1;
A9     ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G7     GOON,2;
       ACT,0,XX(1).EQ.0,A8;
       ACT,0,,A0;
A8     ASSIGN,XX(5)=TNOW-XX(4);
       ACT,0,,DT;
A0     ASSIGN,XX(1)=XX(1)+1;
       TERM;
RPR    QUEUE(1),0,2;
       ACT(2),2520,,G5;
DT     COLCT,XX(5),DOWN TIME;
STOP   TERM;
       END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
FIN;
```

ORU Name: Engine Cntrlr.   QPA: 2   MTBF: 87600
Distribution: Normal   Shape Parameter: N/A
Standard Deviation: 10% of MTBF

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
        XX(1),INST_QTY/
        XX(2),FAIL/
        XX(3),GS;
INTLC,INST_QTY=2;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=2;
TIMST,XX(1),INST_QTY HGM,3/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1     CREATE,RNORM(87600,8760,1);
        ACT,0,INST_QTY.LT.1,STOP;
        ACT,0,,G1;
CP2     CREATE,RNORM(87600,8760,2);
        ACT,0,INST_QTY.LT.2,STOP;
        ACT,0,,G1;
G1      GOON,1;
        ASSIGN,INST_QTY=INST_QTY-1;
        ASSIGN,XX(6)=XX(6)-1;
        ASSIGN,FAIL=FAIL+1,1;
        ACT,0,INST_QTY.EQ.0,A1;
        ACT,0,INST_QTY.GE.1,ORU;
A1      ASSIGN,XX(4)=TNOW;
        ACT,0,,ORU;
ORU     COLCT,INT(1),ORU_FAIL;
G2      GOON,1;
        ACT,0,GS.GE.1,G3;
        ACT,2160,GS.LE.0,RPR;
G3      GOON,2;
        ACT,0,,A2;
        ACT,4680,,G5;
A2      ASSIGN,GS=GS-1;
        ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G4      GOON,1;
        ACT,0,INST_QTY.EQ.0,A6;
        ACT,0,INST_QTY.GE.1,A7;
A6      ASSIGN,XX(5)=TNOW-XX(4);
        ASSIGN,XX(1)=XX(1)+1;
        ACT,0,,DT;
A7      ASSIGN XX(1)=XX(1)+1;
        TERM;
G5      GOON,1;
        ACT,0,XX(6).LT.2,G8;
        ACT,0,XX(6).EQ.2,A4;
A4      ASSIGN,GS=GS+1;
        TERM;
G6      GOON,1;
A9      ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G7      GOON,2;
        ACT,0,XX(1).EQ.0,A8;
        ACT,0,,A0;
A8      ASSIGN,XX(5)=TNOW-XX(4);
        ACT,0,,DT;
A0      ASSIGN,XX(1)=XX(1)+1;
        TERM;
RPR     QUEUE(1),0,2;
        ACT(2),2520,,G5;

STOP    TERM;
        END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
FIN;
```

ORU Name: Engine Cntrlr.   QPA: 2   MTBF: 87600
Distribution: Weibull   Shape Parameter: (0.7)
Standard Deviation: N/A

```
GEN,TMILLS,FAILURES,7/4/88,20,,,,,,Y,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
       XX(1),INST_QTY/
       XX(2),FAIL/
       XX(3),GS;
INTLC,INST_QTY=2;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=2;
TIMST,XX(1),INST_QTY HGM,3/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1    CREATE,WEIBL(87600,0.7,1);
       ACT,0,INST_QTY.LT.1,STOP;
       ACT,0,,G1;
CP2    CREATE,WEIBL(87600,0.7,2);
       ACT,0,INST_QTY.LT.2,STOP;
       ACT,0,,G1;
G1     GOON,1;
       ASSIGN,INST_QTY=INST_QTY-1;
       ASSIGN,XX(6)=XX(6)-1;
       ASSIGN,FAIL=FAIL+1,1;
       ACT,0,INST_QTY.EQ.0,A1;
       ACT,0,INST_QTY.GE.1,ORU;
A1     ASSIGN,XX(4)=TNOW;
       ACT,0,,ORU;
ORU    COLCT,INT(1),ORU_FAIL;
G2     GOON,1;
       ACT,0,GS.GE.1,G3;
       ACT,2160,GS.LE.0,RPR;
G3     GOON,2;
       ACT,0,,A2;
       ACT,4680,,G5;
A2     ASSIGN,GS=GS-1;
       ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G4     GOON,1;
       ACT,0,INST_QTY.EQ.0,A6;
       ACT,0,INST_QTY.GE.1,A7;
A6     ASSIGN,XX(5)=TNOW-XX(4);
       ASSIGN,XX(1)=XX(1)+1;
       ACT,0,,DT;
A7     ASSIGN XX(1)=XX(1)+1;
       TERM;
G5     GOON,1;
       ACT,0,XX(6).LT.2,G8;
       ACT,0,XX(6).EQ.2,A4;
A4     ASSIGN,GS=GS+1;
       TERM;
G6     GOON,1;
A9     ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G7     GOON,2;
       ACT,0,XX(1).EQ.0,A8;
       ACT,0,,A0;
A8     ASSIGN,XX(5)=TNOW-XX(4);
       ACT,0,,DT;
A0     ASSIGN,XX(1)=XX(1)+1;
       TERM;
RPR    QUEUE(1),0,2;
       ACT(2),2520,,G5;

STOP   TERM;
       END;
INIT,0,438000;
FIN;
```

```
ORU Name: Linear Actuator        QPA: 4    MTBF: 57000
Distribution: Exponential        Shape Parameter: N/A
Standard Deviation: N/A
```

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
       XX(1),INST_QTY/
       XX(2),FAIL/
       XX(3),GS;
INTLC,INST_QTY=4;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=4;
TIMST,XX(1),INST_QTY HGM,5/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1    CREATE,EXPON(57000,1);
       ACT,0,INST_QTY.LT.1,STOP;
       ACT,0,,G1;
CP2    CREATE,EXPON(57000,2);
       ACT,0,INST_QTY.LT.2,STOP;
       ACT,0,,G1;
CP3    CREATE,EXPON(57000,3);
       ACT,0,INST_QTY.LT.3,STOP;
       ACT,0,,G1;
CP4    CREATE,EXPON(57000,4);
       ACT,0,INST_QTY.LT.4,STOP;
       ACT,0,,G1;
G1     GOON,1;
       ASSIGN,INST_QTY=INST_QTY-1;
       ASSIGN,XX(6)=XX(6)-1;
       ASSIGN,FAIL=FAIL+1,1;
       ACT,0,INST_QTY.EQ.0,A1;
       ACT,0,INST_QTY.GE.1,ORU;
A1     ASSIGN,XX(4)=TNOW;
       ACT,0,,ORU;
ORU    COLCT,INT(1),ORU_FAIL;
G2     GOON,FIN;
       ACT,0,GS.GE.1,G3;
       ACT,2160,GS.LE.0,RPR;
G3     GOON,2;
       ACT,0,,A2;
       ACT,4680,,G5;
A2     ASSIGN,GS=GS-1;
       ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G4     GOON,1;
       ACT,0,INST_QTY.EQ.0,A6;
       ACT,0,INST_QTY.GE.1,A7;
A6     ASSIGN,XX(5)=TNOW-XX(4);
       ASSIGN,XX(1)=XX(1)+1;
       ACT,0,,DT;
A7     ASSIGN,XX(1)=XX(1)+1;
       TERM;
G5     GOON,1;
       ACT,0,XX(6).LT.4,G6;
       ACT,0,XX(6).EQ.4,A4;
A4     ASSIGN,GS=GS+1;
       TERM;
G6     GOON,1;
A9     ASSIGN,XX(6)=XX(6)+1;
       ACT,2160;
G7     GOON,2;
       ACT,0,XX(1).EQ.0,A8;
       ACT,0,,A0;
A8     ASSIGN,XX(5)=TNOW-XX(4);
       ACT,0,,DT;
A0     ASSIGN,XX(1)=XX(1)+1;
       TERM;
RPR    QUEUE(1),0,4;
       ACT(4),2520,,G5;
DT     COLCT,XX(5),DOWN TIME;
STOP   TERM;
       END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
```

ORU Name: Linear Actuator QPA: 4 MTBF: 57000
Distribution: Normal Shape Parameter: N/A
Standard Deviation: 10% of MTBF

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
      XX(1),INST_QTY/
      XX(2),FAIL/
      XX(3),GS;
INTLC,INST_QTY=4;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=4;
TIMST,XX(1),INST_QTY HGM,5/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1   CREATE,RNORM(57000,2850,1);
      ACT,0,INST_QTY.LT.1,STOP;
      ACT,0,,G1;
CP2   CREATE,RNORM(57000,2850,2);
      ACT,0,INST_QTY.LT.2,STOP;
      ACT,0,,G1;
CP3   CREATE,RNORM(57000,2850,3);
      ACT,0,INST_QTY.LT.3,STOP;
      ACT,0,,G1;
CP4   CREATE,RNORM(57000,2850,4);
      ACT,0,INST_QTY.LT.4,STOP;
      ACT,0,,G1;
G1    GOON,1;
      ASSIGN,INST_QTY=INST_QTY-1;
      ASSIGN,XX(6)=XX(6)-1;
      ASSIGN,FAIL=FAIL+1,1;
      ACT,0,INST_QTY.EQ.0,A1;
      ACT,0,INST_QTY.GE.1,ORU;
A1    ASSIGN,XX(4)=TNOW;
      ACT,0,,ORU;
ORU   COLCT,INT(1),ORU_FAIL;
G2    GOON,FIN;
      ACT,0,GS.GE.1,G3;
      ACT,2160,GS.LE.0,RPR;
G3    GOON,2;
      ACT,0,,A2;
      ACT,4680,,G5;
A2    ASSIGN,GS=GS-1;
      ASSIGN,XX(6)=XX(6)+1;
      ACT,2160;
G4    GOON,1;
      ACT,0,INST_QTY.EQ.0,A6;
      ACT,0,INST_QTY.GE.1,A7;
A6    ASSIGN,XX(5)=TNOW-XX(4);
      ASSIGN,XX(1)=XX(1)+1;
      ACT,0,,DT;
A7    ASSIGN,XX(1)=XX(1)+1;
      TERM;
G5    GOON,1;
      ACT,0,XX(6).LT.4,G6;
      ACT,0,XX(6).EQ.4,A4;
A4    ASSIGN,GS=GS+1;
      TERM;
G6    GOON,1;
A9    ASSIGN,XX(6)=XX(6)+1;
      ACT,2160;
G7    GOON,2;
      ACT,0,XX(1).EQ.0,A8;
      ACT,0,,A0;
A8    ASSIGN,XX(5)=TNOW-XX(4);
      ACT,0,,DT;
A0    ASSIGN,XX(1)=XX(1)+1;
      TERM;
RPR   QUEUE(1),0,4;
      ACT(4),2520,,G5;
DT    COLCT,XX(5),DOWN TIME;
STOP  TERM;
      END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
```

ORU Name: Linear Actuator   **QPA:** 4   **MTBF:** 57000
Distribution: Weibull   **Shape Parameter:** (0.7)
Standard Deviation: N/A

```
GEN,TMILLS,FAILURES,7/4/88,20,,,,,,Y,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
      XX(1),INST_QTY/
      XX(2),FAIL/
      XX(3),GS;
INTLC,INST_QTY=4;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=4;
TIMST,XX(1),INST_QTY HGM,5/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1     CREATE,WEIBL(57000,0.7,1);
        ACT,0,INST_QTY.LT.1,STOP;
        ACT,0,,G1;
CP2     CREATE,WEIBL(57000,0.7,2);
        ACT,0,INST_QTY.LT.2,STOP;
        ACT,0,,G1;
CP3     CREATE,WEIBL(57000,0.7,3);
        ACT,0,INST_QTY.LT.3,STOP;
        ACT,0,,G1;
CP4     CREATE,WEIBL(57000,0.7,4);
        ACT,0,INST_QTY.LT.4,STOP;
        ACT,0,,G1;
G1      GOON,1;
        ASSIGN,INST_QTY=INST_QTY-1;
        ASSIGN,XX(6)=XX(6)-1;
        ASSIGN,FAIL=FAIL+1,1;
        ACT,0,INST_QTY.EQ.0,A1;
        ACT,0,INST_QTY.GE.1,ORU;
A1      ASSIGN,XX(4)=TNOW;
        ACT,0,,ORU;
ORU     COLCT,INT(1),ORU_FAIL;
G2      GOON,1;
        ACT,0,GS.GE.1,G3;
        ACT,2160,GS.LE.0,RPR;
G3      GOON,2;
        ACT,0,,A2;
        ACT,4680,,G5;
A2      ASSIGN,GS=GS-1;
        ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G4      GOON,1;
        ACT,0,INST_QTY.EQ.0,A6;
        ACT,0,INST_QTY.GE.1,A7;
A6      ASSIGN,XX(5)=TNOW-XX(4);
        ASSIGN,XX(1)=XX(1)+1;
        ACT,0,,DT;
A7      ASSIGN,XX(1)=XX(1)+1;
        TERM;
G5      GOON,1;
        ACT,0,XX(6).LT.4,G6;
        ACT,0,XX(6).EQ.4,A4;
A4      ASSIGN,GS=GS+1;
        TERM;
G6      GOON,1;
A9      ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G7      GOON,2;
        ACT,0,XX(1).EQ.0,A8;
        ACT,0,,A0;
A8      ASSIGN,XX(5)=TNOW-XX(4);
        ACT,0,,DT;
A0      ASSIGN,XX(1)=XX(1)+1;
        TERM;
RPR     QUEUE(1),0,4;
        ACT(4),2520,,G5;
DT      COLCT,XX(5),DOWN TIME;
STOP    TERM;
        END;
INIT,0,438000;
FIN;
```

```
ORU Name: Transformer        QPA: 8    MTBF: 87600
Distribution: Exponential    Shape Parameter: N/A
Standard Deviation: N/A
```

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
        XX(1),INST_QTY/
        XX(2),FAIL/
        XX(3),GS;
INTLC,INST_QTY=8;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=8;
TIMST,XX(1),INST_QTY HGM,9/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1     CREATE,EXPON(87600,1);
        ACT,0,INST_QTY.LT.1,STOP;
        ACT,0,,G1;
CP2     CREATE,EXPON(87600,2);
        ACT,0,INST_QTY.LT.2,STOP;
        ACT,0,,G1;
CP3     CREATE,EXPON(87600,3);
        ACT,0,INST_QTY.LT.3,STOP;
        ACT,0,,G1;
CP4     CREATE,EXPON(87600,4);
        ACT,0,INST_QTY.LT.4,STOP;
        ACT,0,,G1;
CP5     CREATE,EXPON(87600,5);
        ACT,0,INST_QTY.LT.5,STOP;
        ACT,0,,G1;
CP6     CREATE,EXPON(87600,6);
        ACT,0,INST_QTY.LT.6,STOP;
        ACT,0,,G1;
CP7     CREATE,EXPON(87600,7);
        ACT,0,INST_QTY.LT.7,STOP;
        ACT,0,,G1;
CP8     CREATE,EXPON(87600,8);
        ACT,0,INST_QTY.LT.8,STOP;
        ACT,0,,G1;
G1      GOON,1;
        ASSIGN,INST_QTY=INST_QTY-1;
        ASSIGN,XX(6)=XX(6)-1;
        ASSIGN,FAIL=FAIL+1,1;
        ACT,0,INST_QTY.EQ.0,A1;
        ACT,0,INST_QTY.GE.1,ORU;
A1      ASSIGN,XX(4)=TNOW;
        ACT,0,,ORU;
ORU     COLCT,INT(1),ORU_FAIL;
G2      GOON,1;
        ACT.0,GS.GE.1,G3;
        ACT,2160,GS.LE.0,RPR;
G3      GOON,2;
        ACT,0,,A2;
        ACT,4680,,G5;
A2      ASSIGN,GS=GS-1;
        ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G4      GOON,1;
        ACT,0,XX(1).EQ.0,A6;
        ACT,0,XX(1).GE.1,A7;
A6      ASSIGN,XX(5)=TNOW-XX(4);
        ASSIGN,XX(1)=XX(1)+1;
        ACT,0,,DT;
A7      ASSIGN,XX(1)=XX(1)+1;
        TERM;
G5      GOON,1;
        ACT,0,XX(6).LT.8,G6;
        ACT,0,XX(6).GE.8,A4;
A4      ASSIGN,GS=GS+1;
        TERM;
G6      GOON,1;
A9      ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G7      GOON,2;
        ACT,0,XX(1).EQ.0,A8;
        ACT,0,,A0;
A8      ASSIGN,XX(5)=TNOW-XX(4);
        ACT,0,,DT;
A0      ASSIGN,XX(1)=XX(1)+1;
        TERM;
RPR     QUEUE(1),0,8;
        ACT(8),2520,,G5;
DT      COLCT,XX(5),DOWN TIME;
STOP    TERM;
        END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
FIN;
```

ORU Name: Transformer QPA: 8 MTBF: 87600
Distribution: Normal Shape Parameter: N/A
Standard Deviation: 10% of MTBF

```
GEN,TMILLS,FAILURES,7/4/88,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
      XX(1),INST_QTY/
      XX(2),FAIL/
      XX(3),GS;
INTLC,INST_QTY=8;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=8;
TIMST,XX(1),INST_QTY HGM,9/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1     CREATE,RNORM(87600,8760,1);
        ACT,0,INST_QTY.LT.1,STOP;
        ACT,0,,G1;
CP2     CREATE,RNORM(87600,8760,2);
        ACT,0,INST_QTY.LT.2,STOP;
        ACT,0,,G1;
CP3     CREATE,RNORM(87600,8760,3);
        ACT,0,INST_QTY.LT.3,STOP;
        ACT,0,,G1;
CP4     CREATE,RNORM(87600,8760,4);
        ACT,0,INST_QTY.LT.4,STOP;
        ACT,0,,G1;
CP5     CREATE,RNORM(87600,8760,5);
        ACT,0,INST_QTY.LT.5,STOP;
        ACT,0,,G1;
CP6     CREATE,RNORM(87600,8760,6);
        ACT,0,INST_QTY.LT.6,STOP;
        ACT,0,,G1;
CP7     CREATE,RNORM(87600,8760,7);
        ACT,0,INST_QTY.LT.7,STOP;
        ACT,0,,G1;
CP8     CREATE,RNORM(87600,8760,8);
        ACT,0,INST_QTY.LT.8,STOP;
        ACT,0,,G1;
G1      GOON,1;
        ASSIGN,INST_QTY=INST_QTY-1;
        ASSIGN,XX(6)=XX(6)-1;
        ASSIGN,FAIL=FAIL+1,1;
        ACT,0,INST_QTY.EQ.0,A1;
        ACT,0,INST_QTY.GE.1,ORU;
A1      ASSIGN,XX(4)=TNOW;
        ACT,0,,ORU;
ORU     COLCT,INT(1),ORU_FAIL;
G2      GOON,1;
        ACT,0,GS.GE.1,G3;
        ACT,2160,GS.LE.0,RPR;
G3      GOON,2;
        ACT,0,,A2;
        ACT,4680,,G5;
A2      ASSIGN,GS=GS-1;
        ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G4      GOON,1;
        ACT,0,XX(1).EQ.0,A6;
        ACT,0,XX(1).GE.1,A7;
A6      ASSIGN,XX(5)=TNOW-XX(4);
        ASSIGN,XX(1)=XX(1)+1;
        ACT,0,,DT;
A7      ASSIGN,XX(1)=XX(1)+1;
        TERM;
G5      GOON,1;
        ACT,0,XX(6).LT.8,G6;
        ACT,0,XX(6).GE.8,A4;
A4      ASSIGN,GS=GS+1;
        TERM;
G6      GOON,1;
A9      ASSIGN,XX(6)=XX(6)+1;
        ACT,2160;
G7      GOON,2;
        ACT,0,XX(1).EQ.0,A8;
        ACT,0,,A0;
A8      ASSIGN,XX(5)=TNOW-XX(4);
        ACT,0,,DT;
A0      ASSIGN,XX(1)=XX(1)+1;
        TERM;
RPR     QUEUE(1),0,8;
        ACT(8),2520,,G5;
DT      COLCT,XX(5),DOWN TIME;
STOP    TERM;
        END;
INIT,0,8760000;
MONTR,SUMRY,438000,438000;
MONTR,CLEAR,438000,438000;
FIN;
```

ORU Name: Transformer QPA: 8 MTBF: 87600
Distribution: Weibull Shape Parameter: (0.7)
Standard Deviation: N/A

```
GEN,TMILLS,FAILURES,7/4/88,20,,,,,,Y,1;
LIM,1,5,100;
EQUIVALENCE/ATRIB(1),MARK/
      XX(1),INST_QTY/
      XX(2),FAIL/
      XX(3),GS;
INTLC,INST_QTY=8;
INTLC,FAIL=0;
INTLC,GS=1;
INTLC,XX(6)=8;
TIMST,XX(1),INST_QTY HGM,9/0/1;
TIMST,XX(3),GROUND SPARES,4/0/1
NETWORK;
CP1   CREATE,WEIBL(87600,0.7,1);
      ACT,0,INST_QTY.LT.1,STOP;
      ACT,0,,G1;
CP2   CREATE,WEIBL(87600,0.7,2);
      ACT,0,INST_QTY.LT.2,STOP;
      ACT,0,,G1;
CP3   CREATE,WEIBL(87600,0,7,3);
      ACT,0,INST_QTY.LT.3,STOP;
      ACT,0,,G1;
CP4   CREATE,WEIBL(87600,0.7,4);
      ACT,0,INST_QTY.LT.4,STOP;
      ACT,0,,G1;
CP5   CREATE,WEIBL(87600,0.7,5);
      ACT,0,INST_QTY.LT.5,STOP;
      ACT,0,,G1;
CP6   CREATE,WEIBL(87600,0.7,6);
      ACT,0,INST_QTY.LT.6,STOP;
      ACT,0,,G1;
CP7   CREATE,WEIBL(87600,0.7,7);
      ACT,0,INST_QTY.LT.7,STOP;
      ACT,0,,G1;
CP8   CREATE,WEIBL(87600,0.7,8);
      ACT,0,INST_QTY.LT.8,STOP;
      ACT,0,,G1;
G1    GOON,1;
      ASSIGN,INST_QTY=INST_QTY-1;
      ASSIGN,XX(6)=XX(6)-1;
      ASSIGN,FAIL=FAIL+1,1;
      ACT,0,INST_QTY.EQ.0,A1;
      ACT,0,INST_QTY.GE.1,ORU;
A1    ASSIGN,XX(4)=TNOW;
      ACT,0,,ORU;
ORU   COLCT,INT(1),ORU_FAIL;
G2    GOON,1;
      ACT.0,GS.GE.1,G3;
      ACT,2160,GS.LE.0,RPR;
G3    GOON,2;
      ACT,0,,A2;
      ACT,4680,,G5;
A2    ASSIGN,GS=GS-1;
      ASSIGN,XX(6)=XX(6)+1;
      ACT,2160;
G4    GOON,1;
      ACT,0,XX(1).EQ.0,A6;
      ACT,0,XX(1).GE.1,A7;
A6    ASSIGN,XX(5)=TNOW-XX(4);
      ASSIGN,XX(1)=XX(1)+1;
      ACT,0,,DT;
A7    ASSIGN,XX(1)=XX(1)+1;
      TERM;
G5    GOON,1;
      ACT,0,XX(6).LT.8,G6;
      ACT,0,XX(6).GE.8,A4;
A4    ASSIGN,GS=GS+1;
      TERM;
G6    GOON,1;
A9    ASSIGN,XX(6)=XX(6)+1;
      ACT,2160;
G7    GOON,2;
      ACT,0,XX(1).EQ.0,A8;
      ACT,0,,A0;
A8    ASSIGN,XX(5)=TNOW-XX(4);
      ACT,0,,DT;
A0    ASSIGN,XX(1)=XX(1)+1;
      TERM;
RPR   QUEUE(1),0,8;
      ACT(8),2520,,G5;
DT    COLCT,XX(5),DOWN TIME;
STOP  TERM;
      END;
INIT,0,438000;
FIN;
```

Appendix E: Simulation Statistics

This appendix presents the output statistics generated for each simulation. Each simulation has a heading describing the ORU under study, design MTBF, QPA, and the specific distribution. The statistics are arrayed in 20 sequential simulation runs each representing 50 years of Space Station operation.

ORU Name: Eng. Cntrlr.   QPA = 2   MTBF = 87600
Hazard Rate Exponential   Avg. Failures 10

Sim. Runs	System Downtime	#	% Time ORU Operational 0	1	2	% Time Spare In Use 0	1
1	0		0	4.4	95.6	9.6	90.4
2	0		0	1	99	2.1	97.9
3	0		0	4.1	95.9	8.4	91.6
4	2200	1	0.5	3.5	96	6.4	93.6
5	0		0	3.9	96.1	8.5	91.5
6	0		0	7.6	92.4	14.3	85.7
7	0		0	4.9	95.1	10.7	89.3
8	0		0	5.9	94.1	11.3	88.7
9	0		0	6.1	93.9	12.6	87.4
10	0		0	4.4	95.6	9.6	90.4
11	0		0	4.4	95.6	9.6	90.4
12	100	1	0	5.7	94.3	11.4	88.6
13	0		0	8.2	91.8	10.8	89.2
14	0		0	5	95	9.1	90.9
15	0		0	5.4	94.6	11.8	88.2
16	3400	2	0.7	8.1	91.2	13.8	86.2
17	0		0	2.5	97.5	5.3	94.7
18	0		0	5.9	94.1	12.8	87.2
19	0		0	2.5	97.5	5.3	94.7
20	0		0	3.9	96.1	8.5	91.5
Averages	285		0.06	4.87	95.0	9.59	90.4
Std. Dev.	859.		0.18	1.80	1.85	3.00	3.00

ORU Name: Eng. Cntrlr.   QPA = 2   MTBF = 87600
Hazard Rate Normal (std. dev. 05%)   Avg. Failures   10

Sim. Runs	System Downtime	*	% Time ORU Operational 0	1	2	% Time Spare In Use 0	1
1	0		0	4.4	95.6	9.6	90.4
2	0		0	5.4	94.6	11.8	88.2
3	0		0	5	95	10.6	89.4
4	700	1	0.2	5.9	93.9	8.9	91.1
5	0		0	4.9	95.1	10.2	89.8
6	0		0	4.9	95.1	10.7	89.3
7	0		0	4.9	95.1	10.7	89.3
8	0		0	4.9	95.1	10.7	89.3
9	0		0	4.9	95.1	10.7	89.3
10	0		0	4.4	95.6	9.6	90.4
11	0		0	4.9	95.1	10.7	89.3
12	0		0	4.9	95.1	10.7	89.3
13	0		0	4.9	95.1	10.7	89.3
14	0		0	4.9	95.1	10.7	89.3
15	0		0	4.9	95.1	10.7	89.3
16	1400	1	0.3	5.5	94.2	9.5	90.5
17	0		0	4.4	95.6	9.6	90.4
18	0		0	4.9	95.1	9.1	90.9
19	2800	2	0.6	5.5	93.9	8.9	91.1
20	0		0	4.4	95.6	9.6	90.4
Averages	245		0.05	4.94	95.0	10.1	89.8
Std. Dev.	674.		0.14	0.38	0.48	0.75	0.75

ORU Name: Eng. Cntrlr. QPA = 2 MTBF = 87600
Hazard Rate Normal (std. dev. 10%) Avg. Failures 10

Sim. Runs	System Downtime	#	% Time ORU Operational 0	1	2	% Time Spare In Use 0	1
1	0		0	4.4	95.6	9.6	90.4
2	0		0	5.4	94.6	11.8	88.2
3	0		0	4.9	95.1	10.7	89.3
4	0		0	5.4	94.6	11.8	88.2
5	700	1	0.2	5	94.8	9	91
6	0		0	4.8	95.2	10.6	89.4
7	0		0	4.9	95.1	10.7	89.3
8	0		0	4.4	95.6	9.6	90.4
9	0		0	4.5	95.5	9.6	90.4
10	0		0	4.7	95.3	9.9	90.1
11	0		0	4.6	95.4	10.4	89.6
12	0		0	4.9	95.1	10.7	89.3
13	0		0	4.4	95.6	9.6	90.4
14	0		0	4.9	95.1	10.7	89.3
15	0		0	4.9	95.1	10.7	89.3
16	0		0	4.9	95.1	10.7	89.3
17	0		0	4.9	95.1	10.7	89.3
18	0		0	4.9	95.1	10.7	89.3
19	0		0	4.9	95.1	10.7	89.3
20	0		0	4.9	95.1	10.7	89.3
Averages	35		0.01	4.83	95.1	10.4	89.5
Std. Dev.	152.		0.04	0.27	0.28	0.69	0.69

ORU Name: Eng. Cntrlr.   QPA = 2   MTBF = 87600
Hazard Rate Normal (std. dev. 15%) Avg. Failures   10

Sim. Runs	System Downtime	#	% Time ORU Operational 0	1	2	% Time Spare In Use 0	1
1	0		0	4.4	95.6	9.6	90.4
2	0		0	5.4	94.6	11.8	88.2
3	0		0	5.2	94.8	10.9	89.1
4	0		0	5.6	94.4	10.2	89.8
5	0		0	4.6	95.4	10.4	89.6
6	0		0	5.7	94.3	10	90
7	0		0	5.4	94.6	11.8	88.2
8	0		0	4.9	95.1	10.7	89.3
9	0		0	4	96	8.5	91.5
10	100	1	0	5.5	94.5	10.1	89.9
11	0		0	5.4	94.6	10.2	89.8
12	0		0	3.9	96.1	8.5	91.5
13	1100	1	0.2	5.4	94.4	10	90
14	0		0	5.8	94.2	10.8	89.2
15	0		0	4.4	95.6	9.9	90.1
16	0		0	4.9	95.1	10.7	89.3
17	0		0	5.1	94.9	10.5	89.5
18	0		0	4.9	95.1	10.7	89.3
19	0		0	4.9	95.1	10.7	89.3
20	400	1	0.1	5.4	94.5	10.8	89.2
Averages	80		0.01	5.04	94.9	10.3	89.6
Std. Dev.	250.		0.04	0.53	0.54	0.81	0.81

ORU Name: Eng. Cntrlr.   QPA = 2   MTBF = 87600
Hazard Rate Weibull (0.3)   Avg. Failures 2

Sim. Runs	System Downtime	% Time ORU Operational			% Time Spare In Use	
		0	1	2	0	1
1	0	0	1	99	2	98
2	0	0	1	99	2	98
3	0	0	1	99	2	98
4	0	0	1	99	2	98
5	0	0	1	99	2	98
6	0	0	1	99	2	98
7	0	0	1	99	2	98
8	0	0	1	99	2	98
9	0	0	1	99	2	98
10	0	0	1	99	2	98
11	0	0	1	99	2	98
12	0	0	1	99	2	98
13	0	0	1	99	2	98
14	0	0	1	99	2	98
15	0	0	1	99	2	98
16	0	0	1	99	2	98
17	0	0	1	99	2	98
18	0	0	1	99	2	98
19	0	0	1	99	2	98
20	0	0	1	99	2	98
Averages:	0	0	1	99	2	98
Std. Dev.	0	0	0	0	0	0

ORU Name: Eng. Cntrlr. QPA = 2 MTBF = 87600
Hazard Rate Weibull (0.5) Avg. Failures 2

Sim. Runs	System Downtime	% Time ORU Operational			% Time Spare In Use	
		0	1	2	0	1
1	0	0	1	99	2	98
2	0	0	1	99	2	98
3	0	0	1	99	2	98
4	0	0	1	99	2	98
5	0	0	1	99	2	98
6	0	0	1	99	2	98
7	0	0	1	99	2	98
8	0	0	1	99	2	98
9	0	0	1	99	2	98
10	0	0	1	99	2	98
11	0	0	1	99	2	98
12	0	0	1	99	2	98
13	0	0	1	99	2	98
14	0	0	1	99	2	98
15	0	0	1	99	2	98
16	0	0	1	99	2	98
17	0	0	1	99	2	98
18	0	0	1	99	2	98
19	0	0	1	99	2	98
20	0	0	1	99	2	98
Averages	0	0	1	99	2	98
Std. Dev.	0	0	0	0	0	0

ORU Name: Eng. Cntrlr.   QPA = 2   MTBF = 87600
Hazard Rate Weibull (0.7)   Avg. Failures   2

Sim. Runs	System Downtime	% Time ORU Operational			% Time Spare In Use	
		0	1	2	0	1
1	0	0	1	99	2	98
2	0	0	1	99	2	98
3	0	0	1	99	2	98
4	0	0	1	99	2	98
5	0	0	1	99	2	98
6	0	0	1	99	2	98
7	0	0	1	99	2	98
8	0	0	1	99	2	98
9	0	0	1	99	2	98
10	0	0	1	99	2	98
11	0	0	1	99	2	98
12	0	0	1	99	2	98
13	0	0	1	99	2	98
14	0	0	1	99	2	98
15	0	0	1	99	2	98
16	0	0	1	99	2	98
17	0	0	1	99	2	98
18	0	0	1	99	2	98
19	0	0	1	99	2	98
20	0	0	1	99	2	98
Averages	0	0	1	99	2	98
Std. Dev.	0	0	0	0	0	0

ORU Name: L. Act QPA = 4 MTBF = 57000
Hazard Rate Exponential Avg. Failures 30

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0.2	12.1	87.7	26.2	73.8
2	0	0	0	2.5	16.7	80.8	33.6	66.4
3	0	0	0.4	1.4	13.5	84.7	29.2	70.8
4	0	0	0	1	12.5	86.5	29.3	70.7
5	0	0	0	0.9	14.6	84.5	30	70
6	0	0	0	1.8	14	84.2	29.3	70.7
7	0	0	0	1.2	12.9	85.9	25.6	74.4
8	0	0	0	0.1	11.7	88.2	25.5	74.5
9	0	0	0	0.1	11.1	88.8	28.1	71.9
10	0	0	0	1	11.3	87.7	22.9	77.1
11	0	0	0	0.3	14.5	85.2	30.8	69.2
12	0	0	0.5	2.2	8.9	88.4	23	77
13	0	0	0	0.4	12.8	86.8	28	72
14	0	0	0	0.3	12.6	87.1	32	68
15	0	0	0	0.2	9.1	90.7	30.6	69.4
16	0	0	0	0.6	13.3	86.1	33.6	66.4
17	0	0	0	1.4	13.5	85.1	20.5	79.5
18	0	0	0	1.2	14.3	84.5	26.4	73.6
19	0	0	0	0.9	10	89.1	20.3	79.7
20	0	0	0	0.6	13	86.4	29.2	70.8
Averages	0	0	0.04	0.91	12.6	86.4	27.7	72.2
Std. Dev.	0	0	0.13	0.67	1.86	2.15	3.78	3.78

ORU Name: L. Act.   QPA = 4   MTBF = 57000
Hazard Rate   Normal (std. dev. 05%)   Avg. Failures   30

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0.5	10.9	88.6	26.4	73.6
2	0	0	0	0.5	14.9	84.6	27.4	72.6
3	0	0	0	0.5	13.8	85.7	26.3	73.7
4	0	0	0	0.5	13	86.5	29.7	70.3
5	0	0	0	0.6	15.1	84.3	25.4	74.6
6	0	0	0	1.6	14.2	84.2	25.9	74.1
7	0	0	0	1.2	14.2	84.6	28.7	71.3
8	0	0	0	2.4	15.3	82.3	24.2	75.8
9	0	0	0	0	14.8	85.2	29.8	70.2
10	0	0	0	0	14.3	85.7	32.2	67.8
11	0	0	0	0.4	14.1	85.5	31.8	68.2
12	0	0	0	0	14.6	85.4	31.9	68.1
13	0	0	0	0	14.7	85.3	31.7	68.3
14	0	0	0	0.2	14.7	85.1	31.7	68.3
15	0	0	0	2.1	12.5	85.4	27.1	72.9
16	0	0	0	0.6	14.2	85.2	29.6	70.4
17	0	0	0	0.3	14.3	85.4	29.9	70.1
18	0	0	0	0	15.2	84.8	32.9	67.1
19	0	0	0	1.4	12.8	85.8	27.6	72.4
20	0	0	0	0	14.2	85.8	32.4	67.6
Averages	0	0	0	0.64	14.0	85.2	29.1	70.8
Std. Dev.	0	0	0	0.70	1.04	1.13	2.62	2.62

ORU Name: L. Act. QPA = 4 MTBF = 57000
Hazard Rate Normal std. dev. 10%) Avg. Failures 30

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0.4	12.5	87.1	25.7	74.3
2	0	0	0.4	1.7	11.2	86.7	23.9	76.1
3	0	0	0	0.9	13.6	85.5	29.2	70.8
4	0	0	0	0.1	14.3	85.6	31.5	68.5
5	0	0	0	0.5	13.2	86.3	27.5	72.5
6	0	0	0	0.9	13.9	85.2	28.7	71.3
7	0	0	0	0	13.9	86.1	31.9	68.1
8	0	0	0	0.5	13.1	86.4	29.1	70.9
9	0	0	0	0	15	85	33	67
10	0	0	0	0	15.2	84.8	32.7	67.3
11	0	0	0	0.1	14.4	85.5	30.8	69.2
12	0	0	0	1.2	15.1	83.7	29.4	70.6
13	0	0	0	0.3	13.2	86.5	29	71
14	0	0	0	0.1	14	85.9	28.2	71.8
15	0	0	0	0	13.7	86.3	30.4	69.6
16	0	0	0	0.3	13	86.7	29.6	70.4
17	0	0	0	0.6	13.4	86	28.4	71.6
18	0	0	0	0	14.8	85.2	27.6	72.4
19	0	0	0	0	13.4	86.6	29	71
20	0	0	0	0.2	13	86.8	28.1	71.9
Averages	0	0	0.39	13.6	13.6	85.8	29.1	70.8
Std. Dev.	0	0	0.45	0.94	0.94	0.81	2.14	2.14

ORU Name: L. Act. QPA = 4 MTBF = 57000
Hazard Rate Normal (std. dev. 15%) Avg. Failures 30

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0.4	12.1	87.5	25.8	74.2
2	0	0	0	1.9	12.9	85.2	27.4	72.6
3	0	0	0	0.6	11.9	87.5	26.9	73.1
4	0	0	0	0.1	15.3	84.6	32.9	67.1
5	0	0	0	0.2	12.5	87.3	27.3	72.7
6	0	0	0	1.2	12.9	85.9	27.4	72.6
7	0	0	0	0.4	14.9	84.7	31.7	68.3
8	0	0	0	0.5	13.8	85.7	29.1	70.9
9	0	0	0	0.9	12.5	86.6	28	72
10	0	0	0	0	14.5	85.5	31	69
11	0	0	0	1.3	13.7	85	29.7	70.3
12	0	0	0	0.9	14.3	84.8	29.4	70.6
13	0	0	0	1.3	14.1	84.6	29	71
14	0	0	0	0.6	13.4	86	30.2	69.8
15	0	0	0	0.4	12.6	87	28.4	71.6
16	0	0	0	1.5	14	84.5	29.5	70.5
17	0	0	0	1.8	12.1	86.1	27.4	72.6
18	0	0	0	0.9	12.9	86.2	30.1	69.9
19	0	0	0	0.7	13.6	85.7	28.3	71.7
20	0	0	0	0.3	14.9	84.8	31.1	68.9
Averages	0	0	0	0.79	13.4	85.7	29.0	70.9
Std. Dev.	0	0	0	0.53	0.99	0.98	1.75	1.75

ORU Name: L. Act.   QPA = 4   MTBF 57000
Hazard Rate   Weibull (0.3)   Avg. Failures: 3

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0	1	99	3	97
2	0	0	0	0	1	99	3	97
3	0	0	0	0	1	99	3	97
4	0	0	0	0	1	99	3	97
5	0	0	0	0	1	99	3	97
6	0	0	0	0	1	99	3	97
7	0	0	0	0	1	99	3	97
8	0	0	0	0	1	99	3	97
9	0	0	0	0	1	99	3	97
10	0	0	0	0	1	99	3	97
11	0	0	0	0	1	99	3	97
12	0	0	0	0	1	99	3	97
13	0	0	0	0	1	99	3	97
14	0	0	0	0	1	99	3	97
15	0	0	0	0	1	99	3	97
16	0	0	0	0	1	99	3	97
17	0	0	0	0	1	99	3	97
18	0	0	0	0	1	99	3	97
19	0	0	0	0	1	99	3	97
20	0	0	0	0	1	99	3	97
Averages	0	0	0	0	1	99	3	97
Std. Dev.	0	0	0	0	0	0	0	0

ORU Name: L. Act.   QPA = 4   MTBF 57000
Hazard Rate   Weibull (0.5)   Avg. Failures: 3

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0	1	99	3	97
2	0	0	0	0	1	99	3	97
3	0	0	0	0	1	99	3	97
4	0	0	0	0	1	99	3	97
5	0	0	0	0	1	99	3	97
6	0	0	0	0	1	99	3	97
7	0	0	0	0	1	99	3	97
8	0	0	0	0	1	99	3	97
9	0	0	0	0	1	99	3	97
10	0	0	0	0	1	99	3	97
11	0	0	0	0	1	99	3	97
12	0	0	0	0	1	99	3	97
13	0	0	0	0	1	99	3	97
14	0	0	0	0	1	99	3	97
15	0	0	0	0	1	99	3	97
16	0	0	0	0	1	99	3	97
17	0	0	0	0	1	99	3	97
18	0	0	0	0	1	99	3	97
19	0	0	0	0	1	99	3	97
20	0	0	0	0	1	99	3	97
Averages	0	0	0	0	1	99	3	97
Std. Dev.	0	0	0	0	0	0	0	23.4

ORU Name: L. Act.   QPA = 4   MTBF = 57000
Hazard Rate   Weibull (0.7)   Avg. Failures: 3

Sim. Runs	System Downtime	% Time ORU Operational					% Time Spare In Use	
		0	1	2	3	4	0	1
1	0	0	0	0	2	98	4	96
2	0	0	0	0	1	99	3	97
3	0	0	0	0	1	99	3	97
4	0	0	0	0	1	99	3	97
5	0	0	0	0	1	99	3	97
6	0	0	0	0	1	99	3	97
7	0	0	0	0	1	99	3	97
8	0	0	0	0	1	99	3	97
9	0	0	0	0	1	99	3	97
10	0	0	0	0	1	99	3	97
11	0	0	0	0	1	99	3	97
12	0	0	0	0	1	99	3	97
13	0	0	0	0	1	99	3	97
14	0	0	0	0	1	99	3	97
15	0	0	0	0	1	99	3	97
16	0	0	0	0	1	99	3	97
17	0	0	0	0	1	99	3	97
18	0	0	0	0	1	99	3	97
19	0	0	0	0	1	99	3	97
20	0	0	0	0	1	99	3	97
Averages	0	0	0	0	1.05	98.9	3.05	96.9
Std. Dev.	0	0	0	0	0.217	0.21	0.21	2.13

ORU Name: Trans. QPA = 8 MTBF 87600
Hazard Rate Exponential Avg. Failures 38

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0	0.8	1.8	17.7	79.7	34.5	65.5
2	0	0	0	0	0	0	0	2.8	20.6	76.6	43.5	56.5
3	0	0	0	0	0	0	0.1	1.3	14.8	83.8	35.3	64.7
4	0	0	0	0	0	0	0	0.7	15	84.3	36.5	63.5
5	0	0	0	0	0	0	0.2	3.3	17.6	78.9	40.1	59.9
6	0	0	0	0	0	0	0	0.5	15	84.5	29.5	70.5
7	0	0	0	0	0	0	0.7	1.7	14.2	83.4	30.3	69.7
8	0	0	0	0	0	0.1	0	0.8	16.9	82.2	34.3	65.7
9	0	0	0	0	0	0	0	1	17.6	81.4	35.4	64.6
10	0	0	0	0	0	0	0.4	2.3	17.7	79.6	37.1	62.9
11	0	0	0	0	0	0	0.2	0.7	15.7	83.4	32.4	67.6
12	0	0	0	0	0	0.1	0	2.4	20.4	77.1	41.3	58.7
13	0	0	0	0	0	0.1	0.6	2.2	19.8	77.3	32.1	67.9
14	0	0	0	0	0	0	0.3	1.9	16.3	81.5	42.6	57.4
15	0	0	0	0	0	0	0	1.1	14.9	84	34.6	65.4
16	0	0	0	0	0	0	0	1.9	19.2	78.9	30	70
17	0	0	0	0	0	0	0	1.7	15	83.3	38.2	61.8
18	0	0	0	0	0	0	0.4	2.5	17.4	79.7	33.4	66.6
19	0	0	0	0	0	0	0	0	12	88	38.1	61.9
20	0	0	0	0	0	0	0.2	1.8	15.7	82.3	27.7	72.3
Averages	0	0	0	0	0	0.01	0.19	1.62	16.6	81.4	35.3	64.6
Std. Dev.	0	0	0	0	0	0.03	0.25	0.82	2.17	2.88	4.29	4.29

ORU Name: Trans. OPH = 8 MTBF 87600
Hazard Rate Normal (std. dev. 05%) Avg. Failures 40

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0.3	0.6	1.6	14.2	83.3	29.9	70.1
2	0	0	0	0	0	0	0	0.4	16.7	82.9	38	62
3	0	0	0	0	0	0	0	1.5	17.4	81.1	35.4	64.6
4	0	0	0	0	0	0	0	1.2	18	80.8	36.7	63.3
5	0	0	0	0	0	0	0	0.5	18.3	81.2	40.2	59.8
6	0	0	0	0	0	0	0.1	1.3	16.7	81.9	35.2	64.8
7	0	0	0	0	0	0	0	0.9	17.4	81.7	36.2	63.8
8	0	0	0	0	0	0	0	0.4	18.7	80.9	39.1	60.9
9	0	0	0	0	0	0	0	0.6	17.7	81.7	38.2	61.8
10	0	0	0	0	0	0	0	0.6	17.7	81.7	37	63
11	0	0	0	0	0	0	0.3	2.1	17.1	80.5	35.9	64.1
12	0	0	0	0	0	0	0	2.7	14.1	83.2	29.1	70.9
13	0	0	0	0	0	0	0	2.6	16.4	81	30.4	69.6
14	0	0	0	0	0	0	0	4	13.3	82.7	36	64
15	0	0	0	0	0	0	0	3.1	15.7	81.2	35	65
16	0	0	0	0	0	0	0	1.4	17.5	81.1	36.5	63.5
17	0	0	0	0	0	0	0.1	2	16.7	81.2	34.7	65.3
18	0	0	0	0	0	0	0	0.5	18.2	81.3	34	66
19	0	0	0	0	0	0	0.2	2.7	15.3	81.8	35.3	64.7
20	0	0	0	0	0	0	0	1.6	17	81.4	33.2	66.8
Averages	0	0	0	0	0	0.01	0.06	1.58	16.7	81.6	35.3	64.7
Std. Dev.	0	0	0	0	0	0.06	0.14	1.02	1.44	0.78	2.83	2.83

ORU Name: Trans. QPA = 8 MTBF 87600
Hazard Rate Normal (std. dev. 10%) Avg. Failures 40

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0.1	1	2.7	13.4	82.8	31.2	68.8
2	0	0	0	0	0	0	0	1	18.4	80.6	38.5	61.5
3	0	0	0	0	0	0	0	0.7	18.4	80.9	36.1	63.9
4	0	0	0	0	0	0	0.2	1.3	16.6	81.9	35.8	64.2
5	0	0	0	0	0	0	0	1	16.9	82.1	34	66
6	0	0	0	0	0	0	0	0.6	16.9	82.5	36.2	63.8
7	0	0	0	0	0	0	0	0.9	17	82.1	36	64
8	0	0	0	0	0	0	0.3	1.9	18.3	79.5	37.7	62.3
9	0	0	0	0	0	0	0.1	2.3	16.2	81.4	32.8	67.2
10	0	0	0	0	0	0	0	1	17.5	81.5	35.2	64.8
11	0	0	0	0	0	0	0.1	0.9	17.9	81.1	37.3	62.7
12	0	0	0	0	0	0	0	2.2	14.3	83.5	31.4	68.6
13	0	0	0	0	0	0	0	1.7	16.2	82.1	36.1	63.9
14	0	0	0	0	0	0	0	1.6	16.9	81.5	34.7	65.3
15	0	0	0	0	0	0	0	1	18.7	80.3	37.2	62.8
16	0	0	0	0	0	0	0	1.1	18	80.9	37	63
17	0	0	0	0	0	0	0	0.5	14.3	85.2	32.7	67.3
18	0	0	0	0	0	0	0	2	17.1	80.9	36.2	63.8
19	0	0	0	0	0	0	0.3	2.8	16.1	80.8	37.4	62.6
20	0	0	0	0	0	0	0	1.4	18.6	80	36.1	63.9
Averages	0	0	0	0	0	0.00	0.1	1.43	16.8	81.5	35.4	64.5
Std. Dev.	0	0	0	0	0	0.02	0.22	0.67	1.46	1.25	2.02	2.02

ORU Name: Trans.   OPA = 8   MTBF 87600
Hazard Rate   Normal (std. dev. 15%)   Avg. Failures 40

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0	0.7	1.5	13.9	83.9	31.8	68.2
2	0	0	0	0	0	0	0	0.7	18.1	81.2	37.4	62.6
3	0	0	0	0	0	0	0	1.1	17.6	81.3	37.6	62.4
4	0	0	0	0	0	0	0	1.7	15.9	82.4	32.7	67.3
5	0	0	0	0	0	0	0	2.2	16.1	81.7	32.7	67.3
6	0	0	0	0	0	0	0	2.5	16.8	80.7	35.3	64.7
7	0	0	0	0	0	0	0	1.7	16.5	81.8	33.4	66.6
8	0	0	0	0	0	0	0.2	2.1	18.5	79.2	37.2	62.8
9	0	0	0	0	0	0	0	1.7	18.1	80.2	34.9	65.1
10	0	0	0	0	0	0	0.3	0.8	16.6	82.3	37.1	62.9
11	0	0	0	0	0	0	0	1.1	17.6	81.3	34.8	65.2
12	0	0	0	0	0	0	0.6	1	18.2	80.2	37.8	62.2
13	0	0	0	0	0	0	0	1.5	18.5	80	38	62
14	0	0	0	0	0	0	0	1.9	16.2	81.9	33.7	66.3
15	0	0	0	0	0	0	0.2	2	15.3	82.5	34	66
16	0	0	0	0	0	0	0	2.1	17.5	80.4	37	63
17	0	0	0	0	0	0	0	1.9	17	81.1	34.2	65.8
18	0	0	0	0	0	0	0	2.7	15.3	82	31.2	68.8
19	0	0	0	0	0	0	0	1.2	16	82.8	36.1	63.9
20	0	0	0	0	0	0	0.2	1.6	16.5	81.7	32.8	67.2
Averages	0	0	0	0	0	0	0.11	1.65	16.8	81.4	34.9	65.0
Std. Dev.	0	0	0	0	0	0	0.20	0.53	1.19	1.08	2.12	2.12

ORU Name: Trans.   OPA = 8   MTBF 87600
Hazard Rate   Weibull (0.3)   Avg. Failures   8

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0	0	1	3	96	7	93
2	0	0	0	0	0	0	0	1	3	96	7	93
3	0	0	0	0	0	0	0	1	3	96	7	93
4	0	0	0	0	0	0	0	1	3	96	7	93
5	0	0	0	0	0	0	0	1	3	96	7	93
6	0	0	0	0	0	0	0	1	3	96	7	93
7	0	0	0	0	0	0	0	1	3	96	7	93
8	0	0	0	0	0	0	0	1	3	96	7	93
9	0	0	0	0	0	0	0	1	3	96	7	93
10	0	0	0	0	0	0	0	1	3	96	7	93
11	0	0	0	0	0	0	0	1	3	96	7	93
12	0	0	0	0	0	0	0	1	3	96	7	93
13	0	0	0	0	0	0	0	1	3	96	7	93
14	0	0	0	0	0	0	0	1	3	96	7	93
15	0	0	0	0	0	0	0	1	3	96	7	93
16	0	0	0	0	0	0	0	1	3	96	7	93
17	0	0	0	0	0	0	0	1	3	96	7	93
18	0	0	0	0	0	0	0	1	3	96	7	93
19	0	0	0	0	0	0	0	1	3	96	7	93
20	0	0	0	0	0	0	0	1	3	96	7	93
Averages	0	0	0	0	0	0	0	1	3	96	7	93
Std. Dev.	0	0	0	0	0	0	0	0	0	0	0	0

ORU Name: Trans.   QPA = 8   MTBF = 87600
Hazard Rate   Weibull (0.5)   Avg. Failures   9

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0	0	1	3	96	7	93
2	0	0	0	0	0	0	0	1	3	96	7	93
3	0	0	0	0	0	0	0	1	3	96	7	93
4	0	0	0	0	0	0	0	1	3	96	7	93
5	0	0	0	0	0	0	0	1	3	96	7	93
6	0	0	0	0	0	0	0	1	3	96	7	93
7	0	0	0	0	0	0	0	1	3	96	7	93
8	0	0	0	0	0	0	0	1	3	96	7	93
9	0	0	0	0	0	0	0	1	3	96	7	93
10	0	0	0	0	0	0	0	1	3	96	7	93
11	0	0	0	0	0	0	0	1	3	96	7	93
12	0	0	0	0	0	0	0	1	3	96	7	93
13	0	0	0	0	0	0	0	1	3	96	7	93
14	0	0	0	0	0	0	0	1	3	96	7	93
15	0	0	0	0	0	0	0	1	3	96	7	93
16	0	0	0	0	0	0	0	1	3	96	7	93
17	0	0	0	0	0	0	0	1	3	96	7	93
18	0	0	0	0	0	0	0	1	3	96	7	93
19	0	0	0	0	0	0	0	1	3	96	7	93
20	0	0	0	0	0	0	0	1	3	96	7	93
Averages	0	0	0	0	0	0	0	1	3	96	7	93
Std. Dev.	0	0	0	0	0	0	0	0	0	0	0	0

ORU Name: Trans.   QPA = 8   MTBF = 87600
Hazard Rate   Weibull (0.7)   Avg. Failures   9

Sim. Runs	System Downtime	% Time ORU Operational									% Time Spare In Use	
		0	1	2	3	4	5	6	7	8	0	1
1	0	0	0	0	0	0	0	1	3	96	7	93
2	0	0	0	0	0	0	0	1	2	97	7	93
3	0	0	0	0	0	0	0	1	2	97	8	92
4	0	0	0	0	0	0	0	1	4	95	7	93
5	0	0	0	0	0	0	0	1	3	96	7	93
6	0	0	0	0	0	0	0	1	3	96	9	91
7	0	0	0	0	0	0	0	1	3	96	9	91
8	0	0	0	0	0	0	0	1	3	96	7	93
9	0	0	0	0	0	0	0	1	4	95	8	92
10	0	0	0	0	0	0	0	1	3	96	9	91
11	0	0	0	0	0	0	0	1	3	96	7	93
12	0	0	0	0	0	0	0	1	3	96	7	93
13	0	0	0	0	0	0	0	1	3	96	7	93
14	0	0	0	0	0	0	0	1	4	95	7	93
15	0	0	0	0	0	0	0	1	3	96	7	93
16	0	0	0	0	0	0	0	1	4	95	7	93
17	0	0	0	0	0	0	0	1	3	96	8	92
18	0	0	0	0	0	0	0	1	2	97	7	93
19	0	0	0	0	0	0	0	1	3	96	9	91
20	0	0	0	0	0	0	0	1	2	97	7	93
Averages	0	0	0	0	0	0	0	1	3	96	7.55	92.4
Std. Dev.	0	0	0	0	0	0	0	0	0.63	0.63	0.80	0.80

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The purpose of this study was to evaluate the Keyspares sparing model used to calculate on-orbit spares for the proposed Space Station. The study had five basic objectives:

1. Present and describe the Keyspares' sparing model and its assumptions.
2. Locate, analyze and discuss the theoretical literature that either supports or refutes the Keyspares' assumptions.
3. Produce a simulation of on-board failures and resupply of the Space Station's Electrical Power Unit (EPU) system.
4. Run the simulation using Keyspares' assumption of a constant Orbital Replaceable Unit (ORU) failure rate and compare the simulation results with recommended ORU stockage policies of the Keyspares model.
5. Run the simulation again while varying the ORU failure rate distributions, and determine the differences resulting from each variation.

The study found that the Keyspares model underestimates the number of spares required to maintain the Space Station's EPU system continuously operational, and recommends that further analysis of the Space Station's sparing requirements and improvements in simulating the Space Station environment be conducted.

Analysis of the simulations found that the Space Station experienced downtime when the EPU ORU failure distributions were assumed to be either normal or exponential, but not for the Weibull distribution (S<1). Also, the study suggests that the level of system redundancy was a driving factor in the amount of system downtime experienced.

Finally, this study recommends that an integrated, "up-front" approach be applied to solving the logistical support problems of the Space Station to ensure mission achievement at the lowest possible cost.